Design of pipeline installation

D-Geo Pipeline

Deltares systems

Deltares

Enabling Delta Life

User Manual

D-GEO PIPELINE

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1 General Information

D-GEO PIPELINE (formerly known as MDrill) has been developed especially for geotechnical engineers and mechanical engineers. D-GEO PIPELINE's graphical interactive interface requires just a short training period for novice users. This means that skills can focus directly on the input of geotechnical and engineering data and on the drilling fluid pressure calculations and strength pipeline calculations.

1.1 Preface

D-GEO PIPELINE is a graphical interactive Windows tool for designing pipelines installed by using one of the three following techniques:

- the horizontal directional drilling (HDD) technique
- the micro-tunneling technique
- the construction in trench technique
- the direct pipe technique

In case of HDD technique, D-GEO PIPELINE can be used to calculate the maximum allowable pressure of the drilling fluid and to assess whether this maximum pressure remains higher than the minimum required drilling pressure. The design is completed by means of a pipe stress analysis.

In case of micro-tunneling, D-GEO PIPELINE can be used to calculate the minimal face support pressure to prevent the possibility of collapse in of the soil in front of the micro tunneling shield and also the maximum face support pressure which should not be exceeded to prevent uplift of the soil above the micro tunneling machine or a blow out of drilling fluid towards the surface.

In case of installation in a trench, D-GEO PIPELINE can be used to check the uplift safety as the soil cover above the pipeline may be insufficient to withstand the buoyant force of an empty pipeline.

In case of direct pipe, D-GEO PIPELINE can be used to calculate the thrust force necessary to install the pipeline. It also calculates the minimal and maximum face support pressure like the micro tunneling method.

Easy and efficient

D-GEO PIPELINE has proved to be a powerful tool in the everyday engineering practice of designing pipelines constructed by means of horizontal directional drilling, micro tunneling or trenching. D-GEO PIPELINE's graphical user interface allows both frequent and infrequent D-GEO PIPELINE users to evaluate the feasibility of pipeline configurations.

Complete functionality

D-GEO PIPELINE provides the complete functionality for the design of pipelines installation.

Product integration

D-GEO PIPELINE is an integrated component of the Deltares Systems. This means that relevant data with MGeoBase (central project database), D-GEO STABILITY formerly known as MStab (stability analysis), MSeep (seepage) and D-SETTLEMENT, formerly known as MSettle (settlements) can be exchanged. MGeobase is used to create and maintain a central project database containing data on the measurements, geometry and soil properties of several cross-sections.
D-GEO PIPELINE also interacts with Scia Pipeline program for advanced structural analysis of pipeline behavior by exporting the D-GEO PIPELINE results in a csv file.

1.2 Installation of pipelines

Pipelines are an important part of the linear infrastructure. They are the lifelines of our modern society. Successful operation of a pipeline system on long term is strongly related to the quality of the engineering works carried out before the installation of the pipeline.

The installation of pipelines is carried out in trenches from times immemorial. After excavation of the trench the pipeline is installed on the bottom of the trench and is subsequently covered by the excavated soil. Since the seventies, last century, other techniques for pipeline installation are introduced. These so called trench less techniques such as horizontal directional drilling and micro tunneling are applied on a large scale since the eighties. A relative new technique is the direct pipe method. They provide a logical alternative when pipelines need to cross roads, railways, dikes, wetlands, rivers and other structures that have to remain intact. These techniques minimize the impact of installation activities in densely populated and economical sensitive areas.

The program D-GEO PIPELINE provides tools for the design of pipeline installation in a trench and trench less, by using the micro tunneling technique , direct pipe technique or the horizontal directional drilling technique. The tools allow the user to minimize the risks during and after installation.

1.2.1 Horizontal Directional Drilling technique

HDD techniqueD-GEO PIPELINE enables the fast design of a pipeline configuration, installed using the horizontal directional drilling technique. With the horizontal directional drilling technique, three installation stages are considered:

- ◇ Pilot drilling
- ◇ Reaming the initial pilot borehole
- ◇ Pulling back the pipeline

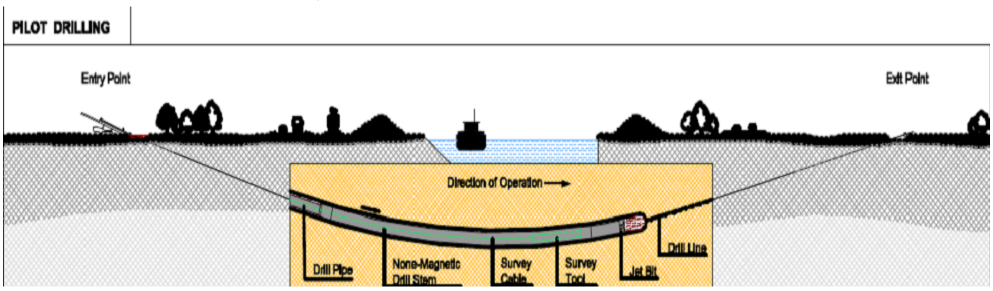


Figure 1.1: *HDD / Pilot drilling (DCA-guidelines)*

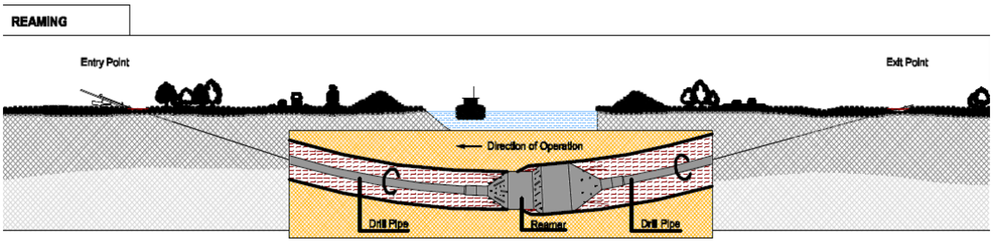


Figure 1.2: *HDD / Pre-reaming (DCA-guidelines)*

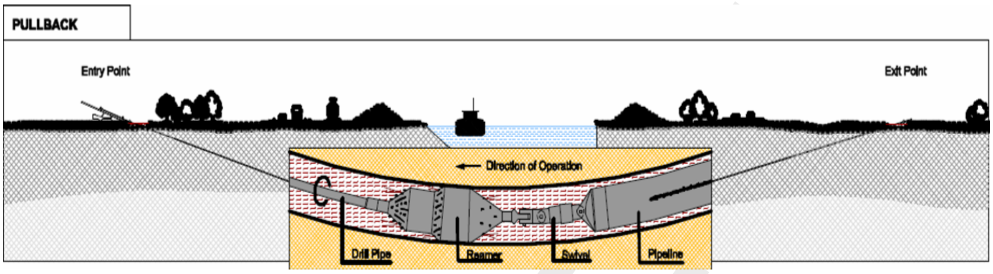


Figure 1.3: *HDD / Pull back operation (DCA-guidelines)*

During the final stage, a drilling is carried out, using a relatively small drill bit, under the object that has to be crossed – for example, a road, railway, waterway or a nature reserve. This initial borehole is called a pilot hole. The diameter of the pilot hole is then enlarged using a reamer. Depending on the required final borehole diameter, the borehole can be enlarged in several stages using reamers of increasing diameters. After reaming, the diameter of the borehole should be 1.3 to 1.5 times larger than the diameter of the pipeline. After preparing the pipeline near the exit point of the borehole, the pipeline is finally pulled into the borehole.

Figure 1.4: *Reamer and cutting wheel*

During all drilling stages, drilling fluid is pumped under pressure into the borehole. The main function of drilling fluid is to transport cuttings from the drilling head through the borehole and to the ground surface. A specific minimum pressure is required for the transport function of the drilling fluid. However, the fluid pressure in the borehole should not exceed a specific maximum value. The maximum value is related to the strength of the soil around the borehole.

If the maximum fluid pressure is exceeded, a 'blow-out' may occur. Besides the pressure of the drilling fluid, other factors play a role in the design process. Both the strength of the pipeline during the pull back operation and the strength of the pipeline in operation need to be sufficient to withstand the forces acting on the pipeline.

1.2.2 Micro Tunneling

Micro tunneling is the technique which uses a micro tunneling boring machine (MTBM) to remove the soil. Micro tunneling usually starts horizontal at a certain level below the surface. Start and reception shafts are created for the micro tunneling machine. In the start shaft a jacking frame and micro tunneling machine in front of pipe sections are installed. The jacks push the pipe elements section by section ahead towards the reception shaft. As the length of the advancing micro tunnel increases, the friction forces along the micro tunneling machine and the pipe segments will increase. Lubrication fluid may be applied to reduce the friction. Very often at the front of the Micro tunneling machine drilling fluid is used for soil removal and front stabilization.

Figure 1.5: *Jacking frame and micro tunneling machine in the start shaft*

1.2.3 Installation in trench

The majority of the underground pipelines are installed in a trench. After excavation of the trench the pipeline is installed on the bottom of the trench (Figure 1.6) and is subsequently covered by the excavated soil. The interaction between the pipe and the condition of the soil material, which is placed back in the trench plays an important role in the engineering of the pipe.

Figure 1.6: *Pipeline installation in a trench*

1.2.4 Direct Pipe method

The direct pipe method enables to lay a prefabricated pipeline in one single, continuous working operation into the ground with the aid of the thrust unit "pipe thrust". As with pipe jacking, earth excavation is executed by means of a navigable micro tunnelling machine, which is directly coupled with the pipeline. The tunnel face is slurry supported; a bentonite suspension is often used for controlled excavation of the soil.

The pipe thruster is fixed horizontally and vertically in the launch pit and clamps the pipeline with its clamping device and pushes it (in front of the pipe the micro tunneling machine is welded) forward through the borehole. Since the diameter of the micro tunnelling machine is significantly larger than the diameter of the pipe a borehole is created. The borehole is filled with lubrication fluid. The type of lubrication fluid is determined by the soil conditions through which the borehole is made.

1.3 Features in standard module (HDD)

In the Netherlands, HDD technique has been used on a large scale since the 1980s. Since the 1970s, Deltares (formerly known as GeoDelft) has been involved in the development and execution of trench less technologies. Years of research have resulted in one of the first design codes for HDD, as well as in a computer program. Since the release of the first version in 1995, D-GEO PIPELINE provides users with the minimum and maximum drilling fluid pressure during the different phases of construction. D-GEO PIPELINE can also analyze the stresses in the pipeline during and after the installation for different pipeline materials.

This section contains an overview of D-GEO PIPELINE's options available for Horizontal Directional Drilling (standard module).

1.3.1 Soil profile

◇ **Multiple layers.** The two-dimensional soil structure can be composed of several soil layers with an arbitrary shape and orientation. Each layer is connected to a particular soil type.

◇ **Verticals.** By placing verticals in the geometry, the coordinates for which output results will be displayed can be defined.

◇ **Soil properties.** The well-established constitutive models are based on common soil parameters for strength and deformation of behavior of specific soil types.

1.3.2 Pipeline materials

D-GEO PIPELINE is capable of dealing with pipelines made of different materials: steel and polyethylene. For both pipe materials, a database containing the material data is available. The database enables a quick re-calculation for alternative material types and dimensions.

1.3.3 Factors

D-GEO PIPELINE applies partial safety factors to the soil parameters (weight, cohesion, friction angle and Young's modulus) and to the loads according either to the NEN series or to the European Standard CEN.

1.3.4 Results

Following the analysis, D-GEO PIPELINE can display results in long table and graphical form.

The tabular report contains:

◇ an echo of the input
◇ soil mechanical calculation results per vertical
◇ drilling fluid pressures calculation results per vertical
◇ pulling force in the pipeline per characteristic point
◇ strength pipeline calculation results
◇ settlement results per vertical

A graphical output of the drilling fluid pressures for all drilling stages and vertical stresses per vertical can also be viewed.

1.4 Features in additional modules

D-GEO PIPELINE comes as a standard module (section 1.3), which can be extended further with other modules to fit three other applications related to pipeline installation:

◇ Micro Tunneling module (section 1.4.1)
◇ Trenching module (section 1.4.2)
◇ Direct Pipe module (section 1.4.3)

1.4.1 Micro Tunneling module

Face support pressures

The micro tunneling machine changes the stress conditions in the soil. The deviations from the original stress conditions are largely determined by the size of the overcut and the applied shield. Small deviations from the original conditions are acceptable as the stability of the soil adjacent to the micro tunneling machine is maintained. A relative low face support pressure may lead to collapse of the soil in front of the shield, which in turn may lead to subsidence of the surface or to settlement of soil layers below a construction or pipeline. A relatively high face support pressure can lead to a blow out of drilling fluid or may lead to heave of the surface.

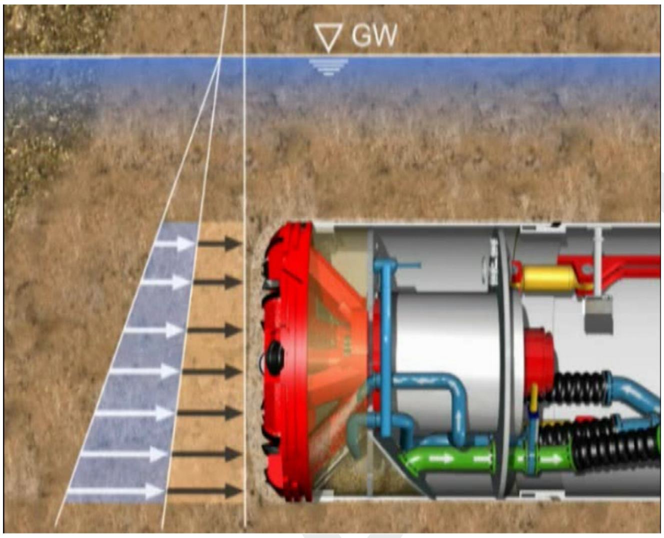


Figure 1.7: *Face support pressures*

While drilling the shield pressures have to be kept between certain limits. To prevent the possibility of collapse in of the soil in front of the micro tunneling shield, causing subsidence, the soil at the front is kept stable by maintaining a minimal face pressure. Depending on the soil type the minimal face support pressure can be calculated using Jancsecz and Steiner theory (Jancesz and Steiner, 1994), or Broms and Bennermark theory (Broms and Bennermark, 1967). A maximum support pressure should not be exceeded to prevent uplift of the soil above the micro tunneling machine or a blow out of drilling fluid towards the surface. The support pressure, the target pressure during drilling should be in between the two limits. At the target pressure, the face support pressure is in equilibrium with the current horizontal soil pressure.

Thrust force

The micro tunneling machine is at the front of the advancing pipe sections. As the length of the advancing micro tunnel increases, the friction forces along the micro tunneling machine and the pipe segments increases. Lubrication fluid may be applied to reduce the friction. D-GEO PIPELINE compares the predicted thrust force with the maximum allowable thrust force of the pipeline.

Surface subsidence

During the micro tunneling drilling process the volume of removed soil is generally larger than the volume of the tunnel (overcut). The volume difference will lead to soil movement towards the borehole, which in turn will lead to surface subsidence. The magnitude of the subsidence (trough) is also calculated.

Arching effect

D-GEO PIPELINE applies a reduced neutral soil load to incorporate the effect of arching. The amount of reduction depends on the depth of the pipeline, diameter and the soil properties. For micro tunneling the effect of arching on the soil load is calculated. Due to the relative small overcut around the borehole arching is not completely developed.

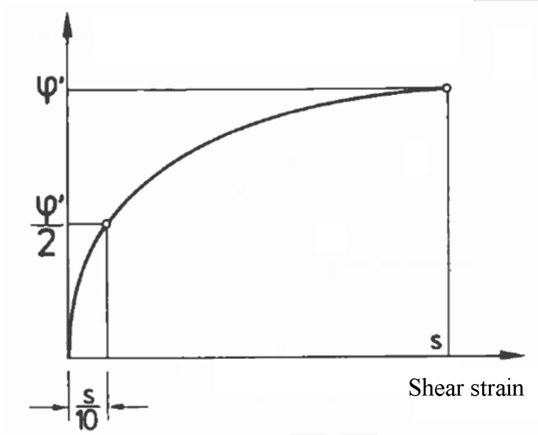


Figure 1.8: *Modelisation of the effect of arching*

Pipeline stress analysis

For pipe stress analysis very often special programs need to be used. These programs need an advanced set of soil mechanical parameters, provided by D-GEO PIPELINE. This will generate a complete spring model around the pipeline for further analysis.

1.4.2 Trenching module

Installation in a trench is the most common way of pipeline installation. In case of pipeline installation in a trench the interaction between the pipe and the soil material, which is placed back in the trench plays an important role in the development of the soil load. Besides the condition of the soil material with which the trench is back-filled, the following parameters determine the soil load for a pipeline in a trench:

- ◇ Dimensions of the trench
- ◇ Soil type in which the trench is excavated
- ◇ Soil type with which the trench is back-filled
- ◇ Unit weight of the soil material with which the trench is back-filled
- ◇ The stiffness of the pipeline

Figure 1.9: *Pipeline installation in trench*

Features

- ◇ Graphical user interface for input of soil data.
- ◇ Advanced input of the ground water pressure distribution.
- ◇ Upheaval and Uplift check.
- ◇ Graphical output of the calculated uplift safety factor.
- ◇ Graphical output of the calculated upheaval safety.
- ◇ 3 dimensional pipeline configuration.
- ◇ Calculation of settlement of the soil layers below the pipeline.
- ◇ Output of soil mechanical parameters for an extensive pipeline stress analysis.

Initial soil load

For advanced pipe stress analyses very often special programs need to be used. These programs need an advanced set of soil mechanical parameters, provided by D-GEO PIPELINE. The programs will generate a complete spring model around the pipeline for further analyses. The soil mechanical parameters include the initial soil load. In the period directly after the installation of the pipeline in the trench, the compaction of the fill plays an important role in the soil pipe interaction. The compaction of the fill leads to differential settlement of the fill above the pipe and adjacent to the pipe.

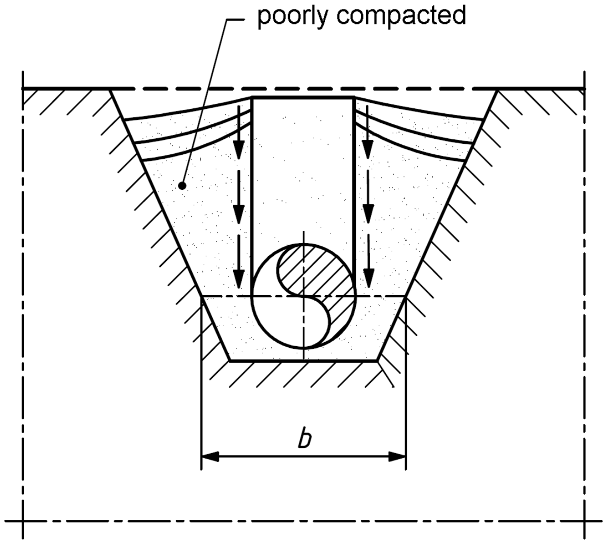


Figure 1.10: *Compaction of the fill after pipeline installation*

Uplift safety

Pipeline installation in wet soft soil environments may lead to buoyant behavior of the pipeline. In case of superficial installation the soil cover above the pipeline may be insufficient to withstand the buoyant force of an empty pipeline.

1.4.3 Direct Pipe module

The thrust force necessary to install the pipeline should be predicted/calculated in the design phase of the project. Since the capacity of the Pipe Thruster is limited, the success of the installation of long pipes is strongly related to the accuracy of the predicted thrust force.

The following mechanisms contribute to the thrust force:

- ◇ Friction of the pipeline behind the thruster on the rollers
- ◇ Friction between pipeline and lubricant fluid
- ◇ Front force at the cutting head of the microtunneling machine
- ◇ Friction between pipeline and the borehole wall
- ◇ Friction due to buckling of the pipe

1.5 History

D-GEO PIPELINE is formerly known as MDrill until version 5.1. This program is a dedicated tool for designing pipelines constructed using the horizontal directional drilling technique (HDD), the micro tunnelingor the construction in trench. Deltares has been developing D-GEO PIPELINE since 1992.

The first successful pipeline installation using the HDD technique Horizontal Directional Drilling was carried out under a river in the US. From 1979 onwards, the HDD technique gradually broke through internationally. The first application in The Netherlands was in 1983/1984 for the construction of a gas pipeline under the Buiten IJ in Amsterdam. Unlike conventional construction methods, the HDD technique can be used to construct pipelines without digging trenches and pits – for example, using sag pipes, pipe jacking or micro tunneling. And it also significantly shortens the construction time.

After the first application of the HDD technique, the NV Nederlandse Gasunie (Dutch Gas Corporation) took the initiative to form a research team to investigate the new construction technique. GeoDelft was a member of that research team, which investigated the construction of two pilot projects in the Netherlands.

The two pilot horizontal directional drillings were carried out in 1985. While the pipeline was being installed, measurements were taken to gain a greater understanding of the behavior of the soil around the borehole. The results of the research were used to define preliminary guidelines that must be taken into account when designing and constructing pipelines using the HDD method.

Since the first pilot projects, a large number of HDD's have been carried out, and the HDD technique has become a quick and reliable method for constructing cables and pipelines under waterways and other objects.

Continuation of the research has led to a greater store of knowledge about soil behavior, the stresses in the pipes, and the fluid pressures in the borehole. The D-GEO PIPELINE computer program was developed on the basis of this knowledge.

MDrill version 1.0 was first released in 1995. Some new features, such as the option for performing a strength calculation, were added in 1998.

MDrill version 4.0 includes an adapted calculation of maximum allowable drilling fluid pressures and an adjusted strength calculation according to the NEN 3650 series.

MDrill version 5.1 includes an adapted calculation of maximum allowable drilling fluid pressures and an adjusted strength calculation according to the new NEN 3650 series. Horizontal curves can be taken into account. The settlement calculation using the Koppejan or the Isotache models is also added. Bundled pipeline are now supported. A library with standard pipes for steel and polyethylene is available. The mud pressure charts have been improved. Exporting soil parameters in versatile format (*.csv) is possible.

D-GEO PIPELINE version 6.1 (2010) includes two new techniques for pipeline installation: the *Micro tunneling* module (section 1.2.2) and the *Construction in trench* module (section 1.2.3). New tutorials (7 to 12) have been added to explain the use of both techniques. Small bugs have been solved: pulling forces for bundled pipes, (horizontal) projected length needed for vertical testing and mud pressure plots, default values for maximum deflection of Steel and PE have been exchanged, factor on modulus of subgrade reaction correctly used, in case of bundles the load angle and bedding angle are given by user (not automatically set to 30 degrees any more), the maximum test pressure is increased. Moreover some minor changes in the report have been made.

D-GEO PIPELINE version 6.2 (2012) includes an adaptation for dead end pipe ("Dead end" pipe has no production phase). Moreover some minor issues have been solved.

D-GEO PIPELINE version 6.3 (2013) includes the following changes: the changes in the Dutch norm NEN 3650:2012 series (NEN, 2012a,b,c) and NEN 3651:2012 (NEN, 2012d) are incorporated, it is possible to add traffic loads, safety factors from the European Standard CEN are added, the report is available in French, the temperature stresses are calculated, the known issue about thrusting forces is solved and the wrong usage of boundaries (for micro-tunneling) is solved.

D-GEO PIPELINE version 14.1 (2014) For micro tunneling, the calculation of the minimum and maximum face support pressures is updated so that the target value is between the minimum

and maximum values. The "Check on calculated stresses for load combination 1 (HDD)" is now correctly performed. The linear settlement coefficient α_g is now a user-defined value in the *Pipe Engineering* window (section 4.6.3.1). For HDD - Strength calculation, the load factor on installation $f_{install}$ is used for the calculation of the axial bending stress σ_b (Equation 25.23).

D-GEO PIPELINE version 15.1 (2015) The default value of the allowable deflection of pipe for steel is changed to 15% (instead of 5%), as prescribed by the NEN. For bundle, the piggability is checked using the diameter of the considered pipe, not the equivalent diameter. A toggle button *Same scale X and Y axis* is implemented in the *Input* and *Top View* windows (Figure 2.1), to switch between same scale for X and Y-axis and not same scale for X and Y-axis. A *Reset* button in the *Defaults* window (Figure 4.47) is added to get the default factors prescribed by the selected norm (NEN or CEN); when a factor differs from the norm, it is displayed in red.

D-GEO PIPELINE version 15.2 (2015) includes a new technique for pipeline installation: the *Direct Pipe* module (section 1.2.4). Two new tutorials (Tutorial 13 in chapter 20 and Tutorial 14 in chapter 21) have been added to explain the use of this technique.

1.6 Minimum System Requirements

The following minimum system requirements are needed in order to run and install the D-GEO PIPELINE software, either from CD or by downloading from the Deltares website via MS Internet Explorer:

- Operating systems:
  - Windows 2003,
  - Windows Vista,
  - Windows 7 – 32 bits
  - Windows 7 – 64 bits
  - Windows 8
- Hardware specifications:
  - 1 GHz Intel Pentium processor or equivalent
  - 512 MB of RAM
  - 400 MB free hard disk space
  - SVGA video card, 1024 $\times$ 768 pixels, High colors (16 bits)
  - CD-ROM drive
  - Microsoft Internet Explorer version 6.0 or newer (download from www.microsoft.com)

1.7 Definitions and Symbols

Co-ordinate system

The horizontal axis is defined as the X axis. The vertical axis is defined to be the Z-direction. Upward is positive and downward negative. Perpendicular to the cross section is the Y direction. The L co-ordinate is the projection of the horizontal co-ordinate X along the pipeline trajectory.

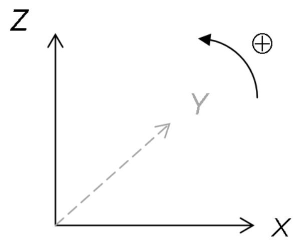


Figure 1.11: *Co-ordinate system*

Geometric data

A	Cross-section of the pipe: $A = \pi \ (r_0^2 - r_\mathrm{i}^2)$	mm^2
D_o	Outer diameter of the pipe	mm
D_eq	Equivalent diameter of the bundled pipeline	mm
D_g	Average diameter of the pipe: $D_\mathrm{g} = D_\mathrm{o} - d_\mathrm{n}$	mm
D_i	Inner diameter of the pipe: $D_\mathrm{i} = D_\mathrm{o} - 2\ d_\mathrm{n}$	mm
d	Minimum wall thickness of the pipe: $d = d_\mathrm{n}\,(1 - \delta_\mathrm{t}/100)$	mm
d_n	Nominal wall thickness of the pipe	mm
$d_\mathrm{n;eq}$	Equivalent nominal wall thickness of a bundled pipeline	mm
I_b	Moment of inertia of the pipe: $I_\mathrm{b} = \pi \ (D_\mathrm{o}^4 - D_\mathrm{i}^4)\ /64$	mm^4
I_w	Moment of inertia of the wall: $I_\mathrm{w} = d_\mathrm{n}^3/12$	mm^4/mm
l_overcut	Difference between the hole radius and the outer radius of the product pipe (micro tunneling)	mm
r_0	Outer radius of the pipe	mm
r_g	Average radius of the pipe	mm
r_i	Inner radius of the pipe	mm
W_b	Resisting moment of the pipe: $W_\mathrm{b} = 2\ I_\mathrm{b}/D_\mathrm{o}$	mm^3
W_w	Resisting moment of the wall: $W_\mathrm{w} = d_\mathrm{n}^2/6$	mm^3/mm
δ_t	Negative wall thickness tolerance	%

Pipe material data

E_b	Young's modulus of the pipe	N/mm^2
R_eb	Yield strength of the steel pipe	N/mm^2
$R_\mathrm{eb;short}$	Yield strength of the polyethylene pipe at sort term	N/mm^2
$R_\mathrm{eb;long}$	Yield strength of the polyethylene pipe at long term	N/mm^2
γ_b	Unit weight of the pipe material	kN/m^3

Process data

p_d	Design pressure	N/mm^2
p_t	Test pressure	N/mm^2
Δt	Temperature variation	K

Pipeline configuration

X_left	X-coordinate of the left point	m
Y_left	Y-coordinate of the left point	m
Z_left	(Vertical) Z-coordinate of the left point	m
X_right	X-coordinate of the right point	m
Y_right	Y-coordinate of the right point	m
Z_right	(Vertical) Z-coordinate of the right point	m

φ_{left}	Left angle of the pipe	radians
φ_{right}	Right angle of the pipe	radians
Z_{lowest}	Lowest level of the pipe	m
R_{left}	Vertical bending radius of the pipe at the left side	m
R_{right}	Vertical bending radius of the pipe at the right side	m
R_{rol}	Bending radius of the rollers	m

Soil properties

a	Adhesion	kN/m^2
a	Direct compression index acc. to Isotache model	–
b	Secular compression index acc. to Isotache model	–
c	Coefficient of secular compression rate acc. to Isotache model	–
c	Cohesion	kN/m^2
c_{u}	Undrained cohesion	kN/m^2
C_{p}	Primary compression coefficient below P_{c}	–
C_{p}'	Primary compression coefficient above P_{c}	–
C_{s}	Secondary compression coefficient below P_{c}	–
C_{s}'	Secondary compression coefficient above P_{c}	–
E	Young's modulus	kN/m^2
G	Shear modulus: $G = E/\left(2\ (1+\nu)\right)$	kN/m^2
OCR	Over-consolidation ratio	–
P_{c}	Preconsolidation pressure	kN/m^2
POP	Pre-overburden pressure	kN/m^2
δ	Friction angle between the soil and the pipeline	Radians
φ	Friction angle	Radians
γ_{unsat}	Unsaturated (dry) unit weight	kN/m^3
γ_{sat}	Saturated (wet) unit weight	kN/m^3
γ_{w}	Unit weight of water	kN/m^3
ν	Poisson's ratio	–

Soil mechanical data

$a_{\text{lub fluid}}$	Adhesion of the lubrification fluid	N/mm^2
B	Width of the foundation element ($= D_{\text{o}}$)	m
B_1	Half width of the covered ground column	m
C	Compression index (soil dependent constant)	–
d_{c}	Depth factor for the effect of the cohesion	–
d_{q}	Depth factor for the effect of the soil cover	–
F_{r}	Permanent friction due to arching effect	N/mm^2
F_{max}	Maximal adhesion	N/mm^2
h	Soil cover above the borehole	m
h_{p}	Soil cover above the borehole in the incompressible layer	m
H	Soil cover above the top of the pipe if the pipe is situated in a compressible layer or thickness of the compressible layer if the pipe is situated in an incompressible layer	m
k_{h}	Horizontal modulus of subgrade reaction	kN/m^3
$k_{\text{v;df}}$	Modulus of subgrade reaction of the drilling fluid	kN/m^3
$k_{\text{v;lub fluid}}$	Modulus of subgrade reaction of the lubrification fluid (micro tunneling)	kN/m^3
$k_{\text{v,pipe}}$	Vertical modulus of subgrade reaction of the pipe	kN/m^3
$k_{\text{v,top}}$	Vertical modulus of subgrade reaction of the soil upward	kN/m^3
$k_{\text{v,bottom}}$	Vertical modulus of subgrade reaction of the soil downward	kN/m^3

K_a	Active earth pressure ratio	–
K_0	Neutral earth pressure ratio: $K_0 = 1 - \sin\varphi$	–
K_c	Load coefficient according to Brinch Hansen	–
K_q	Load coefficient according to Brinch Hansen	–
L	Length of foundation element	m
N_c	Bearing capacity factor for the effect of the cohesion	–
N_q	Bearing capacity factor for the effect of the soil cover	–
N_γ	Bearing capacity factor for the effect of the effective weight of the soil under the foundation surface	–
p_{max}'	Maximum passive vertical stress	N/mm^2
P_{we}	Ultimate vertical bearing capacity	N/mm^2
q_{he}	Horizontal bearing capacity	N/mm^2
$q_{h,n}$	Neutral horizontal stress of the soil	N/mm^2
$q_{h,r}$	Neutral reduced horizontal stress of the soil	N/mm^2
q_k	Initial vertical stress of the soil	N/mm^2
q_n	Neutral vertical stress of the soil	N/mm^2
$q_{n,r}$	Reduced neutral vertical stress of the soil	N/mm^2
$q_{n,r,v}$	Reduced neutral vertical stress increased with a possible traffic load, including safety factors: $q_{n,r,v} = f_{Qn1} \times f_{Qn2} \times (q_{n;r} + f_{qv} \times q_v)$	N/mm^2
q_p	Passive vertical stress of the soil	N/mm^2
$q_{p;max}$	Maximum passive vertical stress	N/mm^2
q_v	Traffic load	N/mm^2
s_c	Shape factor due to cohesion	–
s_q	Shape factor due to soil cover	–
s_γ	Shape factor due to effective weight of the soil under the foundation element	–
W	Maximal axial friction along the pipeline	kN/m
z_{max}	Maximal displacement	m
δ_d	Relative displacement of the soil column	m
$\delta_{lub\ fluid}$	Delta lubrification fluid	Radians
φ_b	Average friction angle over the height of the borehole	Radians
μ	Percentage of compaction depending on the type of fill and type of compaction	–
σ_0'	Effective isotrope stress: $\sigma_0' = (\sigma_v' + \sigma_h')/2$	N/mm^2
σ_c	Vertical effective stress at the compressibility border	N/mm^2
σ_h'	Effective horizontal stress at the pipe center:$\sigma_h' = K \times sigma_v'$	N/mm^2
σ_v'	Effective vertical stress at the pipe center	N/mm^2

Stress analysis data

f_1	Factor of friction between pipe and pipe-rollers	–
f_2	Friction between pipe and drilling fluid	N/mm^2
f_3	Factor of friction between pipe and soil	–
F_{rr}	Direct re-rounding factor	–
F_{rr}'	Indirect re-rounding factor	–
g_t	Curved force	N/mm
K_b	Moment coefficient for directly transmitted stress at the bottom of the pipeline, depending on the bedding angle β	–
K_b'	Moment coefficient for indirectly transmitted stress at the bottom of the pipeline, depending on the bedding angle β	–
K_t	Moment coefficient for directly transmitted stress at the top of the pipeline, depending on the bedding angle β	–

K_t'	Moment coefficient for indirectly transmitted stress at the top of the pipeline, depending on the bedding angle β	–
k_y	Direct deflection factor depending on the bedding angle β	–
k_y'	Indirect deflection factor depending on the bedding angle β	–
L_b	Length of the curved part of the pipeline	mm
L_{rol}	Length of the pipeline on the roller-lane	mm
L_{total}	Length of the pipeline from the entry to the exit point	mm
L_2	Length of the pipeline in the straight part of the borehole	mm
T	Total pulling force in the pipeline	N
T_1	Pulling force due to friction of the pipeline on the roller-lane	N
T_2	Pulling force due to friction between pipe and drilling fluid	N
T_{3a}	Pulling force in the curved part of the borehole due to soil reaction	N
T_{3b}	Pulling force in the curved part of the borehole due to curved forces	N
P_w	Part of pipe filled with fluid during the pull-back operation	%
q_r	Soil reaction	N/mm^2
Q	Weight of the pipeline filled with water	N/mm
Q_{eff}	Effective weight of the pipeline	N/mm
$Q_{filling}$	Weight of the filling (water)	N/mm
Q_{uplift}	Uplift force	N/mm
Q_{pipe}	Weight of the pipeline	N/mm
R	Bending radius	mm
y	Maximum displacement	mm
α	Load angle	Radians
α	Alpha pipe material (for polyethylene)	–
β	Bedding angle	Radians
δ_y	Calculated deflection of the pipe	%
δ_0	Allowable deflection of the pipe	%
δ_1	Allowable deflection of the pipe (piggability)	%
γ_{fill}	Unit weight of the filling fluid	N/mm^3
λ	Characteristic stiffness pipeline-soil	mm^{-1}
σ_b	Axial bending stress	N/mm^2
σ_{pt}	Internal stress around the pipeline caused by test pressure p_t	N/mm^2
σ_{px}	Axial internal stress	N/mm^2
σ_{py}	Internal stress around the pipeline caused by design pressure p_d	N/mm^2
σ_{qn}	Tangential stress (directly transmitted) as a result of the bending	N/mm^2
σ_{qr}	Tangential stress (indirectly transmitted) as a result of the bending	N/mm^2
σ_t	Axial stress due to pull-back	N/mm^2

Drilling fluid data

dp/dz	Flow resistance per unit length of borehole	kN/m^3
f_{loss}	Circulation loss factor	–
h	Height between drilling head and exit point of the drilling fluid	m
L	Distance in the borehole between the drilling head and the exit point of the drilling fluid	m
$p_{max;d}$	Maximum drilling fluid pressure for drained conditions	kN/m^2
$p_{max;und}$	Maximum drilling fluid pressure for undrained conditions	kN/m^2
p_1	Static pressure of the drilling fluid column	kN/m^2
p_2	Excess pressure necessary to maintain the annular flow of drilling fluid with cuttings in the borehole	kN/m^2
Q	Calculated flow rate	m^3/s
Q_{ann}	Annular back-flow rate	m^3/s
Q_{req}	Requested flow rate necessary to initiate flow of drilling fluid	m^3/s

R_b	Radius of the borehole	m
$R_\text{p;max}$	Maximum allowable radius of the plastic zone	m
u	Pore pressure	kN/m^2
$\varepsilon_\text{g;max}$	Maximum deformation of the borehole	–
γ_df	Unit weight of the drilling fluid	kN/m^3
μ_df	Plastic viscosity of the drilling fluid	kN.s/m^2
τ_df	Yield point of the drilling fluid	kN/m^2

Partial safety factors

f_burst	Safety factor on hydraulic heave	–
f_silo	Overburden factor on silo effect	–
f_u	Safety factor on water pressure u	–
f_uplift	Safety factor on uplift	–
$f_{\sigma\text{h}}$	Safety factor on the horizontal effective stress	–
N	Stability ratio for the calculation of the minimal support pressure	–
S	Factor of importance	–
δ_0	Maximum allowable deflection of the pipe	%
δ_1	Maximum allowable deflection of the pipe for piggability	%
$\gamma_\text{imp;long}$	Safety factor on implosion at long term	–
$\gamma_\text{imp;short}$	Safety factor on implosion at short term	–
γ_m	Partial material factor (only for steel).	–
$\gamma_\text{m;test}$	Partial material factor test pressure (only for steel)	–

Contingency factors

f_c	Contingency factor on the cohesion (c or c_u)	–
f_cover	Contingency factor on soil cover	–
f_E	Contingency factor on the Young's modulus E	–
f_k	Overall factor on bending moment: $f_\text{k} = f_\text{M} \times f_\text{install} \times f_\text{R}$	–
f_kv	Contingency factor on the bedding constant k_v	–
f_M	Contingency factor on the bending moment M	–
$f_\text{press;bore}$	Contingency factor on the pressure borehole	–
f_pull	Contingency factor on the pulling force T	–
f_Qn2	Contingency factor on the soil load q_n	–
f_R	Contingency factor on bending radius R	–
f_thrust	Contingency factor on thrsut force	–
f_φ	Contingency factor on the tangent of the friction angle φ	–
f_γ	Contingency factor on the total unit weight γ	–

Load factors

f_install	Load factor on installation	–
f_pd	Load factor on design pressure p_d	–
$f_\text{pd;comb}$	Load factor on design pressure p_d in combination	–
f_pt	Load factor on test pressure p_t	–
f_Qn1	Load factor on soil load q_n	–
f_temp	Load factor on stress due to the temperature variation Δt	–
f_qv	Load factor on traffic load q_v	–

Abbreviations

HDD	Horizontal Directional Drilling
MTBM	Micro Tunneling Boring Machine

PE	Polyethylene
LC	Load Combination

1.8 Getting Help

From the *Help* menu, choose the *Manual* option to open the User Manual of D-GEO PIPELINE in PDF format. Here help on a specific topic can be found by entering a specific word in the *Find* field of the PDF reader.

1.9 Getting Support

Deltares Systems tools are supported by Deltares. A group of 70 people in software development ensures continuous research and development. Support is provided by the developers and if necessary by the appropriate Deltares experts. These experts can provide consultancy backup as well.

If problems are encountered, the first step should be to consult the online Support at: www.deltares.com in menu ‘Software’. Different information about the program can be found on the left-hand side of the window (Figure 1.12):

◇ In ‘Support - Frequentely asked questions’ are listed the most frequently asked technical questions and their answers.
◇ In ‘Support - Known issues’ are listed the issues of the program.
◇ In ‘Release notes D-Geo Pipeline’ are listed the differences between an old and a new version.

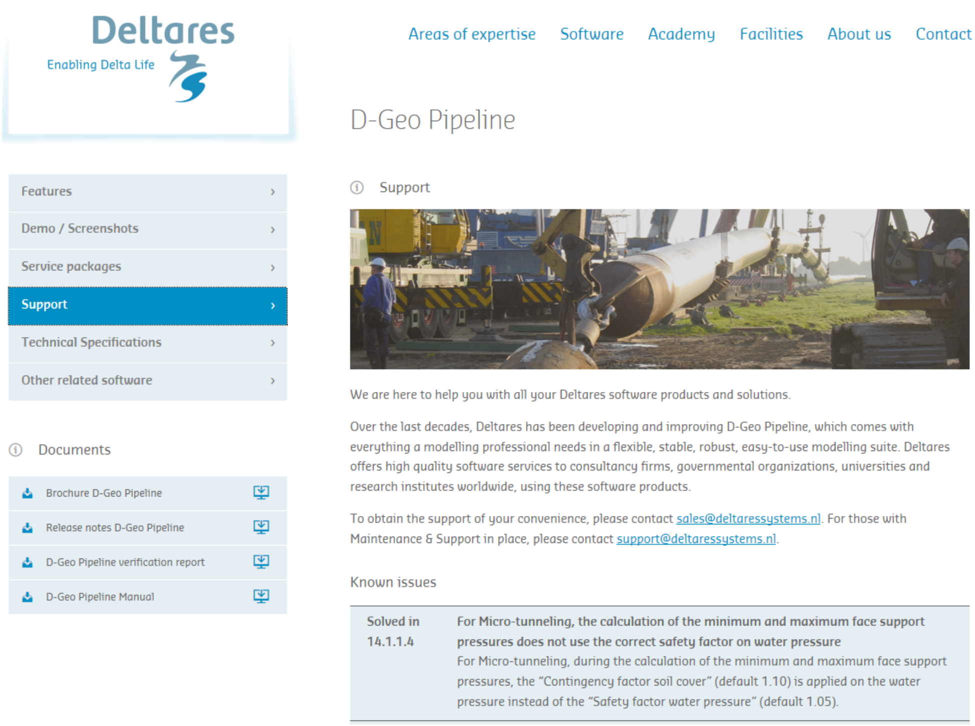


Figure 1.12: *‘Products’ menu of Deltares Systems website (www.deltaressystems.com)*

If the solution cannot be found there, then the problem description can be e-mailed (preferred) or faxed to the Deltares Systems support team. When sending a problem description, please add a full description of the working environment. To do this conveniently:

- ◇ Open the program.
- ◇ If possible, open a project that can illustrate the question.
- ◇ Choose the *Support* option in the *Help* menu. The *System Info* tab contains all relevant information about the system and the DSeries software. The *Problem Description* tab enables a description of the problem encountered to be added.

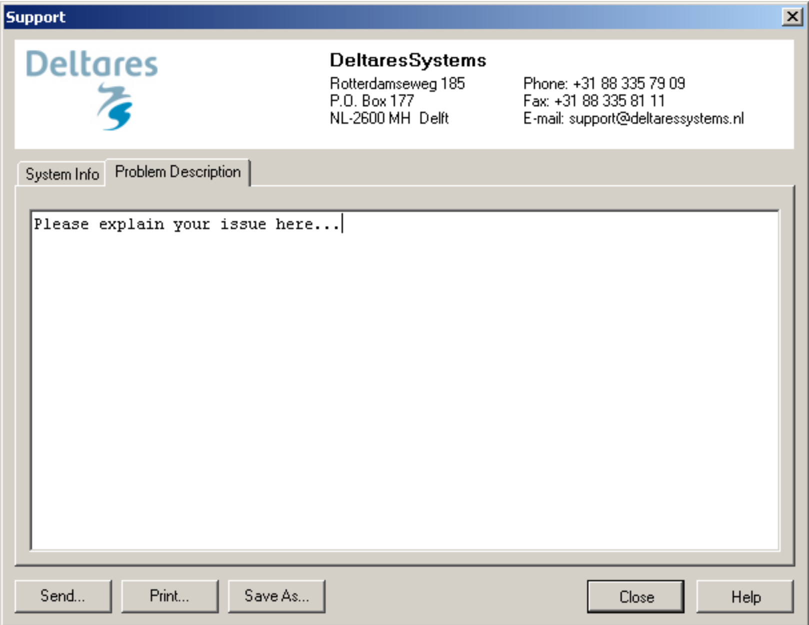


Figure 1.13: *Support window, Problem Description tab*

- ◇ After clicking on the *Send* button, the *Send Support E-Mail* window opens, allowing sending current file as an attachment. Marked or not the *Attach current file to mail* check-box and click *OK* to send it.

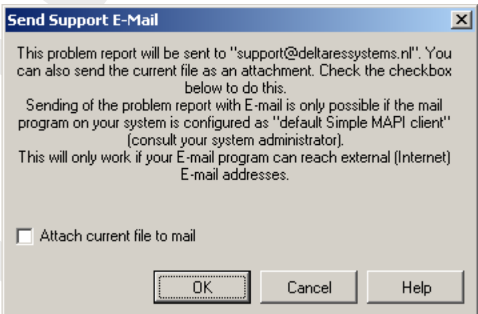


Figure 1.14: *Send Support E-Mail window*

The problem report can either be saved to a file or sent to a printer or PC fax. The document can be emailed to geo.support@deltaressystems.nl or alternatively faxed to +31(0)88 335 8111.

1.10 Deltares

Since January 1st 2008, GeoDelft together with parts of Rijkswaterstaat /DWW, RIKZ and RIZA, WL |Delft Hydraulics and a part of TNO Built Environment and Geosciences are forming the Deltares Institute, a new and independent institute for applied research and specialist advice. Founded in 1934, GeoDelft was one of the world's most renowned institutes for geotechnical and environmental research. As a Dutch national Grand Technological Institute (GTI), Deltares role is to obtain, generate and disseminate geotechnical know-how. The institute is an international leader in research and consultancy into the behavior of soft soils (sand clay and peat) and management of the geo-ecological consequences which arise from these activities. Again and again subsoil related uncertainties and risks appear to be the key factors in civil engineering risk management. Having the processes to manage these uncertainties makes Deltares the obvious partner in risk management for all parties involved in the civil and environmental construction sector. Deltares teams are continually working on new mechanisms, applications and concepts to facilitate the risk management process, the most recent of which is the launch of the concept "GeoQ" into the geotechnical sector.

For more information on Deltares, visit the Deltares website: www.deltares.com.

1.11 Deltares Systems

Deltares Systems (formerly known as Delft GeoSystems) converts Deltares's knowledge into practical geo-engineering services and software. Deltares Systems has developed a suite of software for geotechnical engineering. Besides software, Deltares Systems is involved in providing services such as hosting on-line monitoring platforms, hosting on-line delivery of site investigation, laboratory test results, etc. As part of this process Deltares Systems is progressively connecting these services to their software. This allows for more standardized use of information, and the interpretation and comparison of results. Most software is used as design software, following design standards. This however, does not guarantee a design that can be executed successfully in practice, so automated back-analyses using monitoring information are an important aspect in improving geotechnical engineering results. For more information about Deltares Systems' geotechnical software, including download options, visit www.deltaressystems.com.

1.12 On-line software (Citrix)

Besides purchased software, Deltares Systems tools are available as an on-line service. The input can be created over the internet. Heavy duty calculation servers at Deltares guarantee quick analysis, while results are presented on-line. Users can view and print results as well as locally store project files. Once connected, clients are charged by the hour.
For more information, please contact the Deltares Sales team:
sales@deltaressystems.com.

2 Getting Started

This *Getting Started* chapter aims to familiarize the user with the structure and user interface of D-GEO PIPELINE. The Tutorial section which follows uses a selection of case studies to introduce the program's functions.

2.1 Starting D-GEO PIPELINE

To start D-GEO PIPELINE, click *Start* on the Windows menu bar and then find it under *Programs*, or double-click a D-GEO PIPELINE input file that was generated during a previous session.

For an D-GEO PIPELINE installation based on floating licenses, the *Modules* window may appear at start-up (section 3.2.5). Check that the correct modules are selected and click *OK*.

When D-GEO PIPELINE is started from the Windows menu bar, the last project that was worked on will open automatically, unless the program has been configured otherwise under *Tools: Program Options* (section 3.2).

2.2 Main window

When D-GEO PIPELINE is started, the main window is displayed (Figure 2.1). This window contains a menu bar (section 2.2.1), an icon bar (section 2.2.2), a *View Input* window (section 2.2.3) displaying the pre-selected or most recently accessed project, an info bar (section 2.2.4), a title panel (section 2.2.5) and a status bar (section 2.2.6).

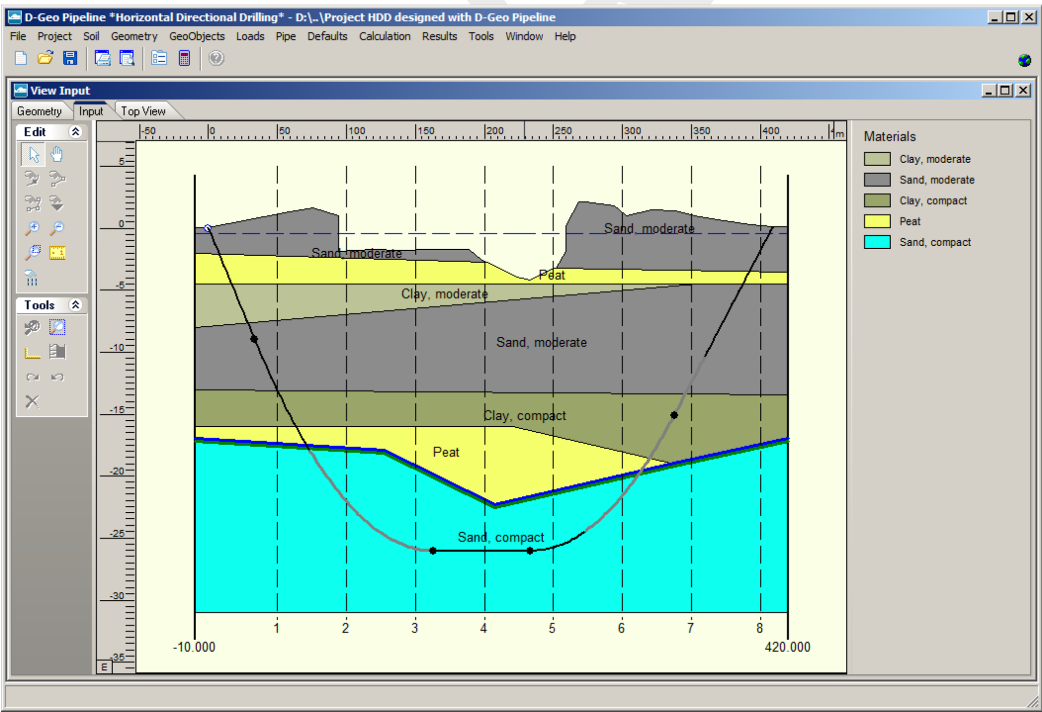


Figure 2.1: *Main Window*

The first time D-GEO PIPELINE is started after installation, the *View Input* window will be closed. When a new file is created, the default model is *Horizontal directional drilling* and the project name is *Project1.*

2.2.1 The menu bar

To access the D-GEO PIPELINE menus, click one of the items on the menu bar.

Figure 2.2: D-GEO PIPELINE *menu bar*

The menus contain the following functions:

File	Standard Windows options for opening, saving and sending files as well as several D-GEO PIPELINE options for exporting and printing the active window and reports (section 3.1).
Project	Definition of the model types, options for *Project Properties* and *View Input File* (section 4.1).
Soil	Definition of soil type properties (section 4.2).
Geometry	Definition of layers, soil types and piezometric lines (section 4.3).
GeoObjects	Definition of the border between compressible top layers and underlying non-compressible soil layers, the border between impermeable and permeable soil layers and definition of the verticals (X-coordinates) for which results will be shown (section 4.4).
Loads	Definition of the traffic loads if present (section 4.5).
Pipe	Definition of the pipeline configuration and input of pipeline parameters (section 4.6).
Defaults	Input of factors (section 4.7).
Calculation	A wide range of calculation options. Determine the settlements and stresses along the verticals (chapter 5).
Results	Graphical or tabular output of the results (chapter 6).
Tools	Options for editing D-GEO PIPELINE program default settings (section 3.2).
Window	Default Windows options for arranging the D-GEO PIPELINE windows and choosing the active window.
Help	Online Help (section 1.8).

2.2.2 The icon bar

The buttons on the icon bar can be used to quickly access frequently used functions (see below).

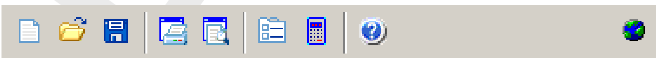
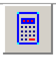


Figure 2.3: D-GEO PIPELINE *icon bar*

Click on the following buttons to activate the corresponding functions:

	Start a new D-GEO PIPELINE project.
	Open the input file of an existing project.
	Save the input file of the current project.
	Print the contents of the active window.

	Display a print preview of the current contents of the *View Input* window.
	Open the *Project Properties* window. Here the project title and other identification data can be entered, and the *View Layout* and *Graph Settings* for the project can be determined.
	Start the calculation.
	Display the contents of online Help.
	Display the first page of the Deltares Systems website: www.deltaressystems.com

2.2.3 View Input

The *View Input* window displays the geometry and additional D-GEO PIPELINE input for the current project. The window has three tabs:

◇ *Geometry*
In this view (Figure 2.4), the positions and soil types of different layers can be defined, inspected and modified. For more information about these general options for geometrical modeling, see chapter 7. See also the description of the *Geometry* menu (section 4.3).

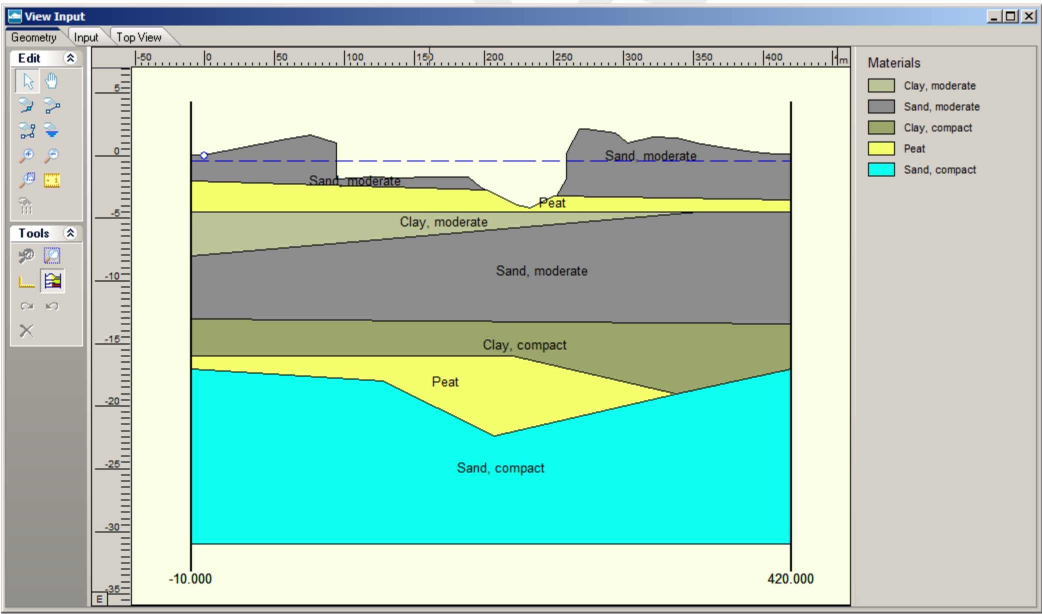


Figure 2.4: *View Input window, Geometry tab*

◇ *Input*
In this view (Figure 2.5), the additional D-GEO PIPELINE-specific input can be defined, inspected and modified. See below in this section for more information about the various options.

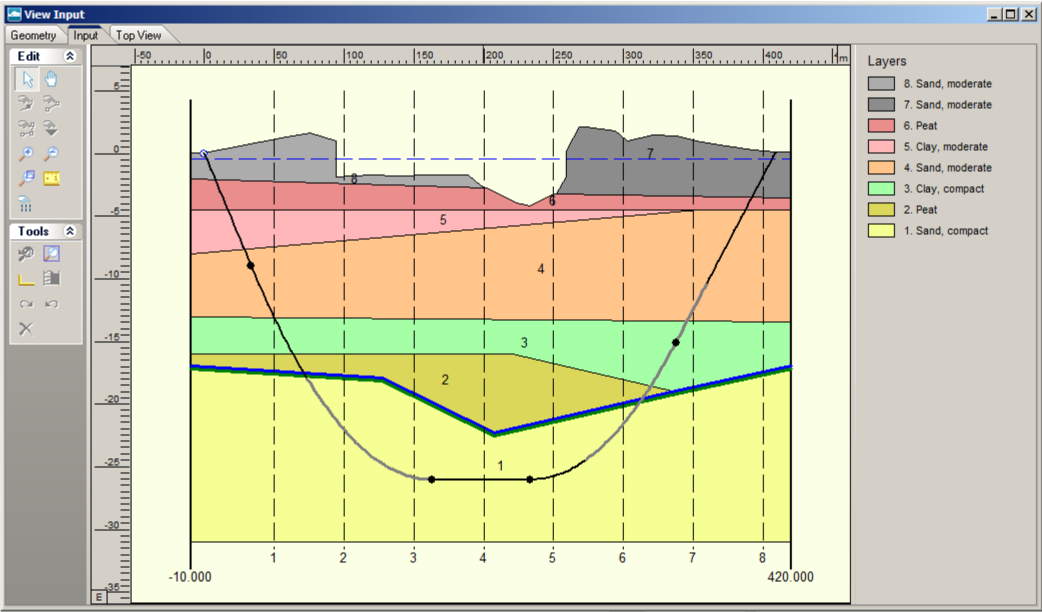


Figure 2.5: *View Input window, Input tab*

◇ *Top View*
In this view (Figure 2.6), the top view of the pipeline longitudinal cross section is shown.

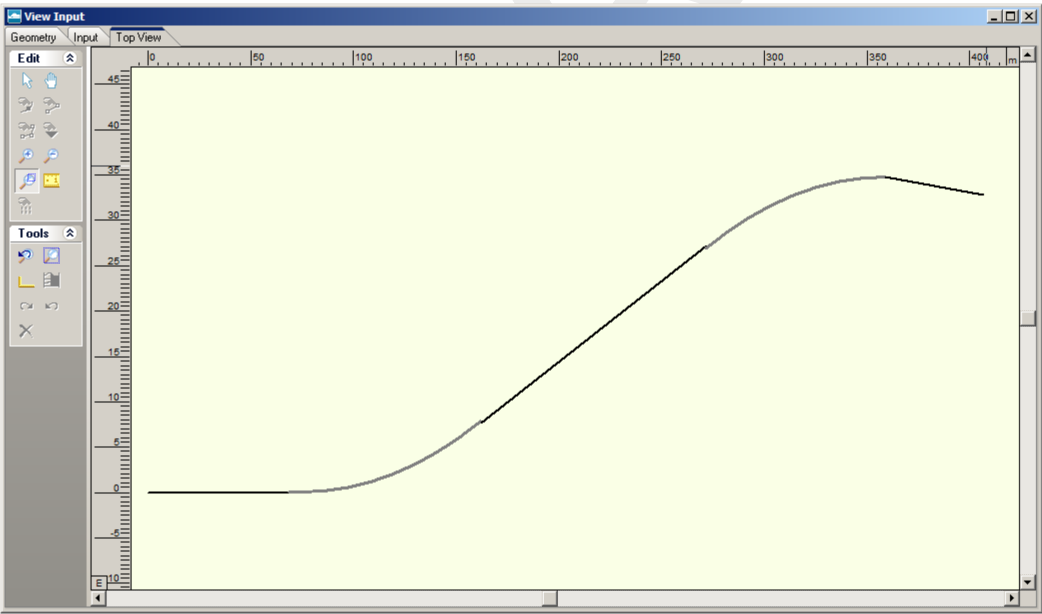
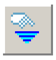
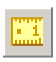


Figure 2.6: *View Input window, Top View tab*

The panel on the left of the view includes buttons for entering data and manipulating the graphical view. Click the following buttons to activate the corresponding functions:

	*Select* and *Edit* mode In this mode, the left-hand mouse button can be used to select a previously-defined verticals or loads in the *View Input* mode. Item can then be deleted or modified by dragging or resizing, or by clicking the right-hand mouse button and choosing options from the menu displayed. Pressing the *Escape* key return the user to this *Select* and *Edit* mode.
	*Pan* button Click this button to change the visible part of the drawing by clicking and dragging the mouse.
	*Add point(s) to boundary / PL-line* Click this button to add points to all types of lines (lines, polylines, boundary lines, PL-lines). By adding a point to a line, the existing line is split into two new lines. This provides more freedom when modifying the geometry.
	*Add single lines(s)* Click this button to add single lines. When this button is selected, the first left-hand mouse click will add the info bar of the new line and a “rubber band” is displayed when the mouse is moved. The second left-hand mouse click defines the end point (and thus the final position) of the line. It is now possible to either go on clicking start and end points to define lines, or stop adding lines by selecting one of the other tool buttons, or by clicking the right-hand mouse button, or by pressing the *Escape* key.
	*Add polyline(s)* Click this button to add poly-lines. When this button is selected, the first left-hand mouse click adds the starting point of the new line and a “rubber band” is displayed when the mouse is moved. A second left-hand mouse click defines the end point (and thus the final position) of the first line in the poly-line and activates the “rubber band” for the second line in the poly-line. Every subsequent left-hand mouse click again defines a new end point of the next line in the poly-line. It is possible to end a poly-line by selecting one of the other tool buttons, or by clicking the right-hand mouse button, or by pressing the *Escape* key.
	*Add PL-line(s)* Click this button to add a piezometric level line (PL-line). Each PL-line must start at the left limit and end at the right limit. Furthermore, each consecutive point must have a strictly increasing X co-ordinate. Therefore, a PL-line must be defined from left to right, starting at the left limit and ending at the right limit. To enforce this, the program will always relocate the first point clicked (left-hand mouse button) to the left limit by moving it horizontally to this limit. If trying to define a point to the left of the previous point, the rubber band icon indicates that this is not possible. Subsequently clicking on the left side of the previous point, the new point will be added at the end of the rubber band icon instead of the position clicked.
	*Zoom in* Click this button to enlarge the drawing, then click the part of the drawing which is to be at the center of the new image. Repeat if necessary.
	*Zoom out* Click this button, then click on the drawing to reduce the drawing size. Repeat if necessary.
	*Zoom rectangle* Click this button then click and drag a rectangle over the area to be enlarged. The selected area will be enlarged to fit the window. Repeat if necessary.
	*Measure the distance between two points* Click this button, then click the first point on the *View Input* window and place the cross on the second point. The distance between the two points can be read at the bottom of the *View Input* window. To turn this option off, click the escape key.

	Add calculation vertical Click this button to graphically define the position of a vertical.
	Undo zoom Click this button to undo the zoom. If necessary, click several times to retrace each consecutive zoom-in step that was made.
	Zoom limits Click this button to display the complete drawing.
	Same scale for X and Y axis Click this button to use the same scale for the horizontal and vertical directions.
	Automatic regeneration of geometry on/off When selected, the program will automatically try to generate a new valid geometry whenever geometry modifications require this. During generation, (poly)lines (solid blue) are converted to boundaries (solid black), with interjacent layers. New layers receive a default material type. Existing layers keep the materials that were assigned to them. Invalid geometry parts are converted to construction elements. Automatic regeneration may slow down progress during input of complex geometry, because validity will be checked continuously.
	Undo Click this button to undo the last change(s) made to the geometry.
	Redo Click this button to redo the previous Undo action.
	Delete Click this button to delete a selected element. Note that this button is only available when an element is selected.

2.2.4 Info bar

This bar situated at the bottom of the *View Input* window displays the co-ordinates of the current position of the cursor and the distance between two points when the icon *Measure the distance between two points* is selected from the *Edit* panel.

2.2.5 Title panel

This panel situated at the bottom of the main window displays the project titles, as entered on the *Identification* tab in the *Project Properties* window (section 4.1.2).

2.2.6 Status bar

This bar situated at the bottom of the main window displays a description of the selected icon of the icon bar (section 2.2.2) or of the *View Input* window (section 2.2.3).

2.3 Files

*.dri	Input file (ASCII): Contains the D-GEO PIPELINE specific input. After interactive generation, this file can be used in subsequent D-GEO PIPELINE analyses.
*.drd	Dump file (ASCII): Contains calculation results used for graphical output.
*.drs	Setting file (ASCII): Working file with settings data. This file does not contain any information that is relevant for the calculation, but only settings that apply to the representation of the data, such as the grid size.
*.drd	Dump file (ASCII): Contains calculation results used for graphical and report output.
*.geo	Input file (ASCII): Contains the geometry data that can be shared with other D-Series programs.
*.set	Working file (ASCII): Contains program settings data.
*.err	If there are any errors in the input, they are described in this file.
*.gef	Measurements data in self describing Geotechnical Exchange Format.

2.4 Tips and Tricks

2.4.1 Keyboard shortcuts

Keyboard shortcuts given in Table 2.5 are another way to reach the features of D-GEO PIPELINE directly without selecting it from the bar menu. These shortcuts are also indicated in the corresponding sub-menus.

Table 2.5: *Keyboard shortcuts for* D-GEO PIPELINE

Keyboard shortcut	Opened window
Ctrl + N	New
Ctrl + O	Open
Ctrl + S	Save
F12	Save As
Shift + Ctrl + C	Copy Active Window to Clipboard
Ctrl + P	Print Report
Ctrl + M	Model
Ctrl + T	Materials
F9	Start Calculation
Ctrl + R	Report
Ctrl + U	Drilling Fluid Pressures Plots

2.4.2 Exporting figures and reports

All figures in D-GEO PIPELINE such as top view and graphical output can be exported in WMF (Windows Meta Files) format. In the *File* menu, select the option *Export Active Window* to save the figures in a file. This file can be later imported in a Word document for example or added as annex in a report. The option *Copy Active Window to Clipboard* from the *File* menu can also be used to copy directly the figure in a Word document.

The report can be entirely exported as PDF (Portable Document Format) or RTF (Rich Text Format) file. To look at a PDF file Adobe Reader can be used. A RTF file can be opened and edited with word processors like MS Word. Before exporting the report, a selection of the relevant parts can be done with the option *Report Selection* (section 6.1).

2.4.3 Copying part of a table

It is possible to select and then copy part of a table in another document (an Excel sheet for example). If the cursor is placed on the left-hand side of a cell of the table, the cursor changes in an arrow which points from bottom left to top right. Select a specific area by using the mouse (see a in Figure 2.7). Then, using the copy button (or ctrl+C) this area can be copied.

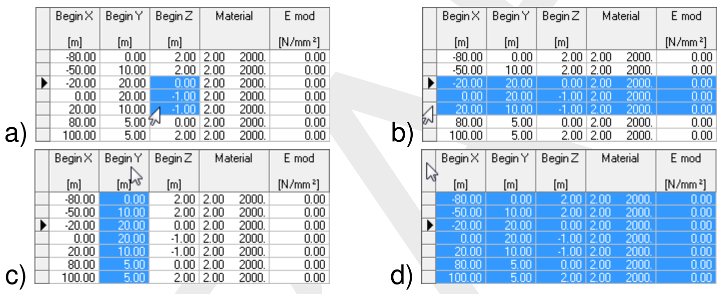


Figure 2.7: *Selection of different parts of a table using the arrow cursor*

To select a row, click on the cell before the row number (see b) in Figure 2.7). To select a column, click on the top cell of the column (see c) in Figure 2.7). To select the complete table, click on the top left cell (see d) in Figure 2.7).

In some tables the buttons *Cut*, *Copy*, and *Paste* are also present at the left hand.

3 General

This chapter contains a detailed description of the available menu options for inputting data for a project, and for calculating and viewing the results. The examples in the Tutorial section provide a convenient starting point for familiarization with the program.

3.1 File menu

3.1.1 General options

Besides the familiar Windows options for opening and saving files, the *File* menu contains a number of options specific to D-GEO PIPELINE:

◇ ***New***
Select this option to display the *New File* window (Figure 3.1). Three choices are available to create a new geometry:

- Select *New geometry* to display the *View Input* window, showing only the geometry limits (with their defaults values) of the geometry;
- Select *New geometry wizard* to create a new geometry faster and easier using the wizard option (involving a step-by-step process for creating a geometry, see section 4.3.2);
- Select *Import geometry* to use an existing geometry.

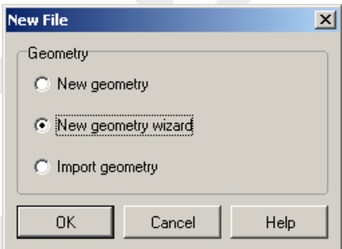


Figure 3.1: *New File window*

◇ ***Copy Active Window to Clipboard***
Use this option to copy the contents of the active window to the Windows clipboard so that they can be pasted into another application. The contents will be pasted in either text format or Windows Meta File format.

◇ ***Export Active Window***
Use this option to export the contents of the active window as a Windows Meta File (*.wmf), a Drawing Exchange File (*.dxf) or a text file (*.txt).

◇ ***Export Report***
This option allows the report to be exported in a different format, such as PDF or RTF.

◇ ***Export Results as xml***
This option allows the inputs and results to be exported in an XML format.

◇ ***Export Results as csv***
This option allows the inputs and results to be exported with the SCIA pipeline wizard in a csv format (Excel). For detailed information, refer to section 3.1.2.

◇ ***Page Setup***
This option allows definition of the way D-GEO PIPELINE plots and reports are to be printed. The printer, paper size, orientation and margins can be defined as well as whether and where axes are required for plots. Click *Autofit* to get D-GEO PIPELINE to choose the best fit for the page.

◇ ***Print Preview Active Window***
This option will display a print preview of the current contents of the *View Input* or *Results* windows.

◇ ***Print Active Window***
This option prints the current contents of the *View Input* or *Results* windows.

◇ ***Print Preview Report***
This option will display a print preview of the calculation report.

◇ ***Print Report***
This option prints the calculation report.

3.1.2 Option "Export Results as csv"

For advanced structural analyses, for example the SCIA Pipeline program (Sci) can be used or an other program. Such a program has advanced options for structural modeling and allows for accurate analyses of stress distribution (Figure 3.2). In order to do so, such a program for an advanced pipe stress analysis needs accurate soil mechanical parameters, which are supplied by D-GEO PIPELINE in a CSV (comma-separated values) format file by means of the option *Export Results as csv* from the *File* menu bar of D-GEO PIPELINE.

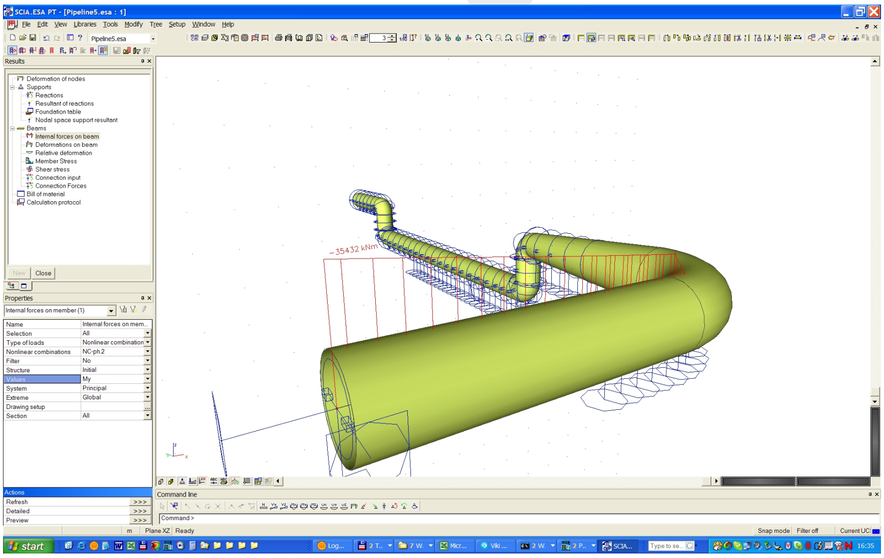


Figure 3.2: *3D configuration in SCIA Pipeline*

The CSV file contains the following data's (calculated without safety factors).

General

Company	[-]	Name of the company who performed the calculation with D-GEO PIPELINE.
Software	[-]	Version number of D-GEO PIPELINE used.

Date	[yyyy/mm/dd]	Date of the calculation with D-GEO PIPELINE.
Time	[hh:mm:ss]	Time of the calculation with D-GEO PIPELINE.

Pipeline data's

P1(x)	[m]	X co-ordinate of the begin point of the pipeline.
P1(y)	[m]	Y co-ordinate of the begin point of the pipeline.
P1(z)	[m]	Z co-ordinate of the begin point of the pipeline.
P2(x)	[m]	X co-ordinate of the end point of the pipeline.
P2(y)	[m]	Y co-ordinate of the end point of the pipeline.
P2(z)	[m]	Z co-ordinate of the end point of the pipeline.
Length Pipe	[m]	Length along the pipeline between the begin point P1 and the end point P2.
Pipe nr	[-]	
Diameter Tube	[mm]	Diameter of the pipe.
Thickness Tube	[mm]	Wall thickness of the pipe.
Material Tube	[-]	

Note: Pipeline data's are not calculated (only user inputted), but are needed in order to prepare the SCIA Pipeline file.

Calculation verticals

Section nr	[-]	Number of the calculation vertical.
x	[m]	X co-ordinate of the calculation vertical.
y	[m]	Y co-ordinate of the calculation vertical.
z	[m]	Z co-ordinate of the calculation vertical.

Horizontal soil mechanical data

From	[m]	Position along the pipeline.
Curved	[boolean]	Presence or not of curved part along the pipeline.
Delta	[m]	Horizontal position of the pipeline measured perpendicular from line P1-P2.
f	[m]	Horizontal settlement of the soil.
Qa	[kN/m^2]	Horizontal active soil pressure.
Qn	[kN/m^2]	Horizontal neutral soil pressure.
Qc	[kN/m^2]	Horizontal consolidation pressure.
Qp	[kN/m^2]	Horizontal passive soil pressure.
C1	[kN/m^3]	Horizontal modulus of subgrade reaction of the soil.
C2	[kN/m^3]	Horizontal modulus of subgrade reaction of the soil.
Gap	[mm]	Gap
UCF(XX)	[-]	Uncertainty on parameter XX.

Note: Horizontal soil mechanical data are given at both left and right sides of the pipe section.

Vertical soil mechanical data

From	[m]	Position along the pipeline.
Curved	[boolean]	Presence or not of curved part along the pipeline.

Delta	[m]	Vertical position of the pipeline measured perpendicular from line P1-P2.
f	[m]	Vertical settlement of the soil.
Qa	[kN/m^2]	Vertical active soil pressure.
Qn	[kN/m^2]	Vertical neutral soil pressure.
Qc	[kN/m^2]	Vertical consolidation pressure.
Qp	[kN/m^2]	Vertical passive soil pressure.
C1	[kN/m^3]	Vertical modulus of subgrade reaction of the soil.
C2	[kN/m^3]	Vertical modulus of subgrade reaction of the soil.
Gap	[mm]	Gap
UCF(XX)	[-]	Uncertainty on parameter XX.

Note: Vertical soil mechanical data are given at both top and bottom sides of the pipe section.

Water

Water height	[mm]	
C1	[kN/m^3]	Unit weight of water.
QP	[kN/m^2]	Water pressure.
UCF(XX)	[-]	Uncertainty on parameter XX.

Axial soil data for friction

From	[m]	Position along the pipeline.
Coef_Mu_x	[-]	Friction coefficient in axial direction.
Cx	[kN/m^3]	Stiffness of the friction spring.
Coef_Mu_rx	[-]	Friction coefficient in axial direction.
Crx	[kN/m^3]	Stiffness of the friction spring.
Factor	[-]	Factor on friction.
UCF(XX)	[-]	Uncertainty on parameter XX.

3.2 Tools menu

On the menu bar, click *Tools* and then choose *Options* to open the *Program Options* window. In this window, the user can optionally define their own preferences for some of the program's default values through the following tabs:

- (section 3.2.1) *View* tab
- (section 3.2.2) *General* tab
- (section 3.2.3) *Locations* tab
- (section 3.2.4) *Language* tab
- (section 3.2.5) *Modules* tab

3.2.1 Program Options - View

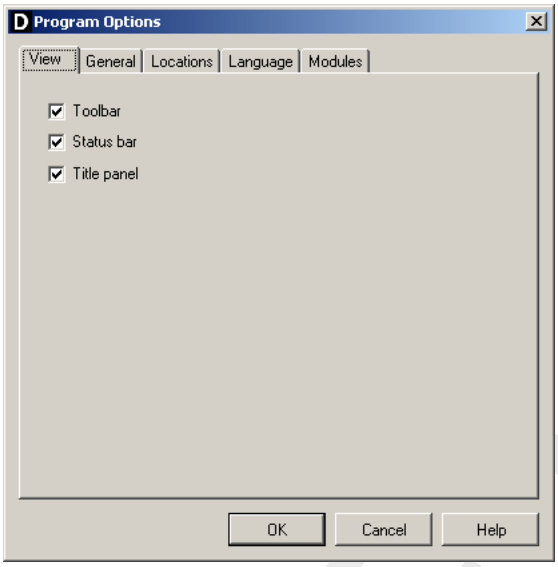


Figure 3.3: *Program Options window, View tab*

Toolbar *Status bar*	Mark the relevant check-box to display the tool bar and/or status bar (section 2.2.6) each time D-GEO PIPELINE is started.
Title panel	Mark this check-box to display the project titles, as entered on the *Identification* tab of the *Project Properties* window (section 4.1.2), in the title panel (section 2.2.5) at the bottom of the *View Input* window.

3.2.2 Program Options - General

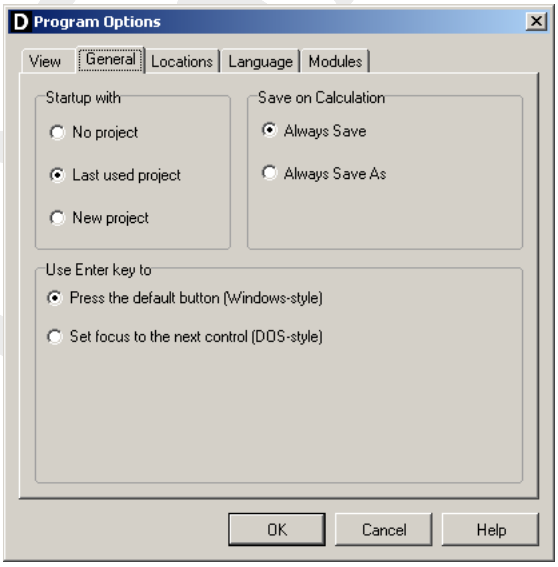


Figure 3.4: *Program Options window, General tab*

Startup with	Click one of these toggle buttons to determine how a project should be initiated each time D-GEO PIPELINE is started. *No project*: Use the buttons in the toolbar or the options in the *File* menu to open an existing project or to start a new one. *Last used project*: The last project to be worked on is opened automatically. *New project*: A new project is created comprising a sheet pile wall with a "dummy" soil layer on both sides. Note that the *Startup with* option is ignored when D-GEO PIPELINE is started by double-clicking on an input file.
Save on Calculation	The toggle buttons determine how input data is saved prior to calculation. It can either be saved automatically, using the same file name each time, or a file name can be specified every time the data is saved.
Use Enter key to	Use the toggle buttons to determine the way the Enter key is used in D-GEO PIPELINE: either as an equivalent of pressing the default button (Windows style) or to shift the focus to the next item in a window (for users accustomed to the DOS version(s) of the program).

3.2.3 Program Options - Locations

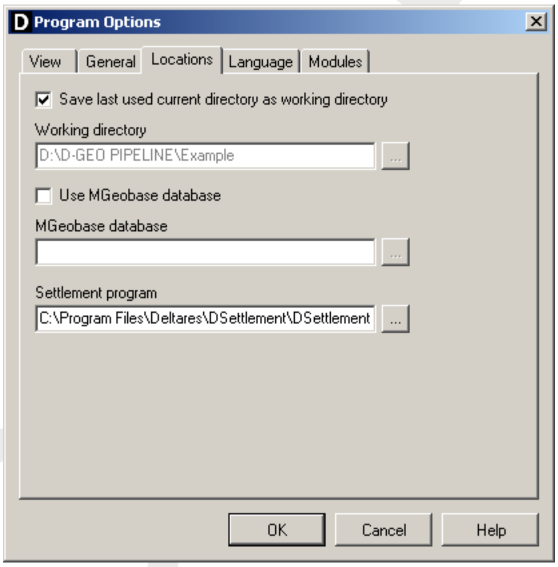


Figure 3.5: *Program Options window, Locations tab*

Working directory	D-GEO PIPELINE will start up with a working directory for selection and saving of files. Either choose to use the last used directory, or specify a fixed path.
Use MGeobase database	Enable this check-box to specify the location of the MGeoBase database with material data, geometric data etc. Use of this option also requires once-off local installation of Interbase client software, assuming that the database is residing on a server on which server software has already been installed.
Settlement program	The calculation of the settlement of the soil layers below the pipeline is performed externally by D-SETTLEMENT (formerly known as MSettle), the settlement calculation program of the Deltares Systems tools. Therefore, the directory where the program is installed must be specified by clicking the *Browse* button.

3.2.4 Program Options - Language

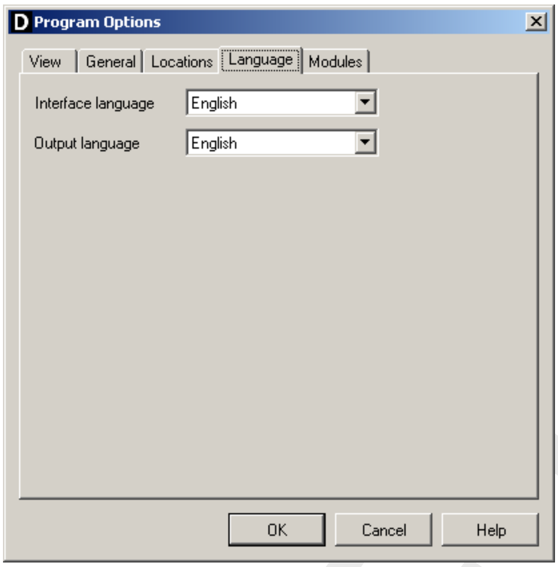


Figure 3.6: *Program Options window, Language tab*

Interface language	Currently, the only available interface language is English.
Output language	The output languages English, German, Dutch and French are supported. The selected output language will be used in all exported reports and output plots.

3.2.5 Program Options - Modules

For a D-GEO PIPELINE installation based on floating licenses, the *Modules* tab can be used to claim a license for the particular modules that are to be used. If the *Show at start of program* check-box is marked then this window will always be shown at start-up.

For a D-GEO PIPELINE installation based on a license dongle, the *Modules* tab will just show the modules that may be used.

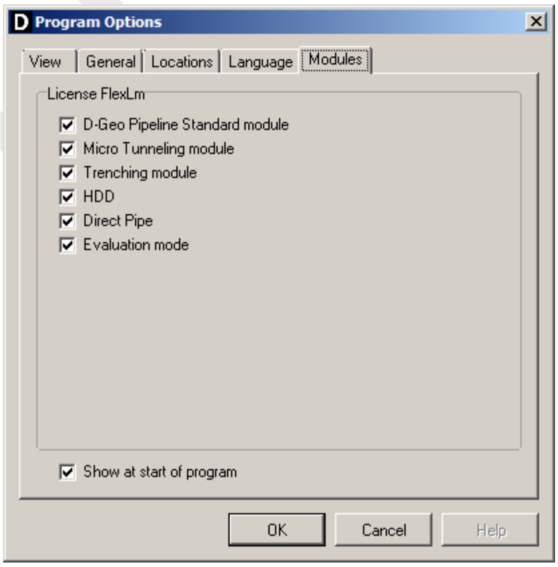


Figure 3.7: *Program Options window, Modules tab*

3.3 Help menu

The *Help* menu allows access to different options.

3.3.1 Error Messages

If errors are found in the input, no calculation can be performed and D-GEO PIPELINE opens the *Error Messages* window displaying more details about the error(s). Those errors must be corrected before performing a new calculation. To view those error messages, select the *Error Messages* option from the *Help* menu. They are also written in the *.err file. They will be overwritten the next time a calculation is started.

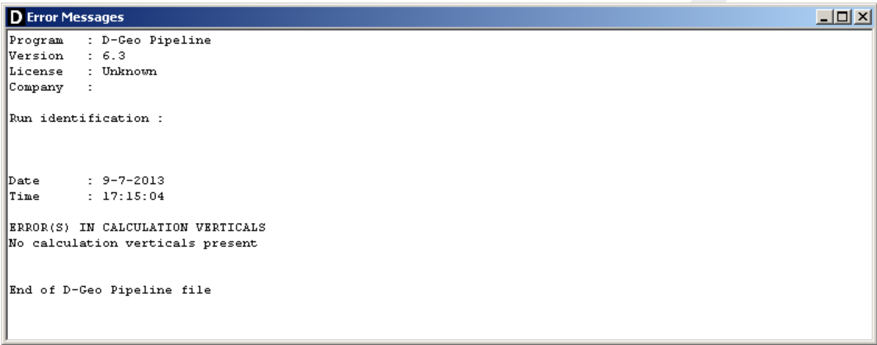


Figure 3.8: *Error Messages window*

3.3.2 Manual

Select the *Manual* option from the *Help* menu to open the User Manual of D-GEO PIPELINE in PDF format. Here help on a specific topic can be found by entering a specific word in the *Find* field of the PDF reader.

3.3.3 Deltares Systems Website

Select *Deltares Systems Website* option from the *Help* menu to visit the Deltares Systems website (www.deltaressystems.com) for the latest news.

3.3.4 Support

Use the *Support* option from the *Help* menu to open the *Support* window in which program errors can be registered. Refer to section 1.9 for a detailed description of this window.

3.3.5 About D-GEO PIPELINE

Use the *About* option from the *Help* menu to display the *About* D-GEO PIPELINE window which provides software information (for example the version of the software).

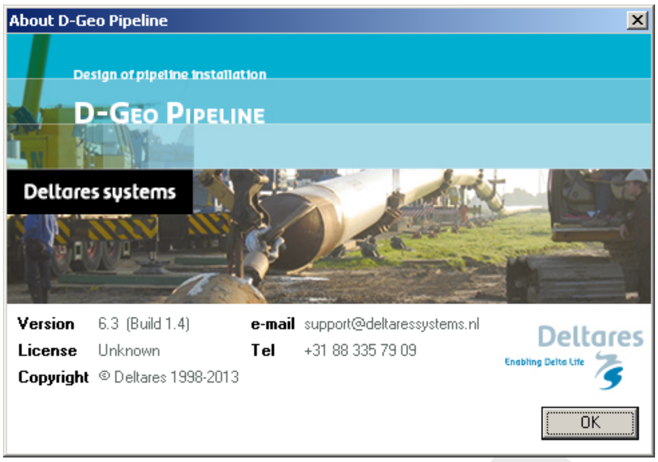


Figure 3.9: *About* D-GEO PIPELINE *window*

4 Input

Before the design calculations can be started, data for the project needs to be input. The examples presented in the Tutorial section (chapter 8) can be a convenient starting point.

4.1 Project menu

On the menu bar (section 2.2.1), click *Project* to display the following menu options:

◇ (section 4.1.1) *Model* to select the required analysis model.
◇ (section 4.1.2) *Properties* to enter a project identification and change the default settings for viewing data.
◇ (section 4.1.3) *View Input File* to inspect the D-GEO PIPELINE ASCII input file.

4.1.1 Model

On the menu bar, click *Project* and then choose *Model* to open the *Model* window.

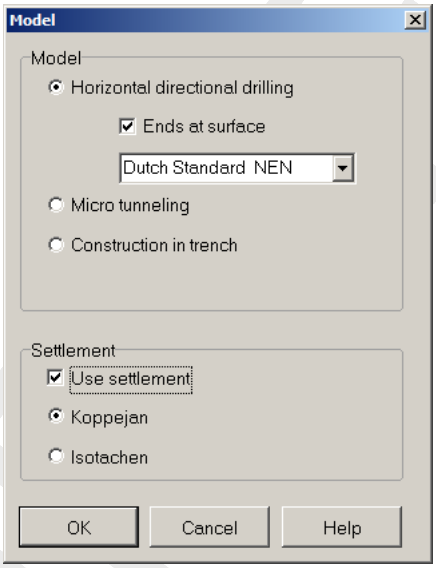


Figure 4.1: *Model window*

Model	Select the technique for pipeline installation: ◇ *Horizontal directional drilling*, see section 1.3; ◇ *Micro tunneling*, see section 1.4.1; ◇ *Construction in trench*, see section 1.4.2; ◇ *Direct pipe*, see section 1.4.3. If *Horizontal directional drilling* is selected, the safety factors according to either the *Dutch Standard NEN* or to the *European Standard CEN* can be applied. For more information, refer to section 4.7.1.1.
Ends at surface	Enable this check-box if the pipeline ends at surface. In this case, D-GEO PIPELINE will automatically calculate the vertical co-ordinate *Z* of the exit point of the pipeline (see section 4.6.1).

Settlement	Enable the check-box *Use settlement* to calculate the vertical displacement of the soil below the pipeline due to installation. D-GEO PIPELINE will use the D-SETTLEMENT computer program. The required settlement model (*Koppejan* or *Isotache*) must be selected. For background information, see section 23.10.2 and section 23.10.1 respectively for Koppejan and Isotache models. **Note:** The check-box *Use settlement* is available only when the program D-SETTLEMENT (formerly known as MSettle) is installed, and when the location of the executable (DSettlement.exe) is specified in the *Locations* tab of the *Program Options* window (section 3.2.3). **Note:** The pipeline settlement can also be entered manually (if available) in the *Calculation Verticals* window (refer to section 4.4.2).

4.1.2 Project Properties

On the menu bar, click *Project* and then choose *Properties* to open the input window. The *Project Properties* window has two tabs, which allow the settings for the current project to be changed:

◇ *Identification*, to specify project identification data.
◇ *View Input*, to define the appearance of items in the *View Input* window.

Project Properties - Identification

Use the *Identification* tab to specify the project identification data:

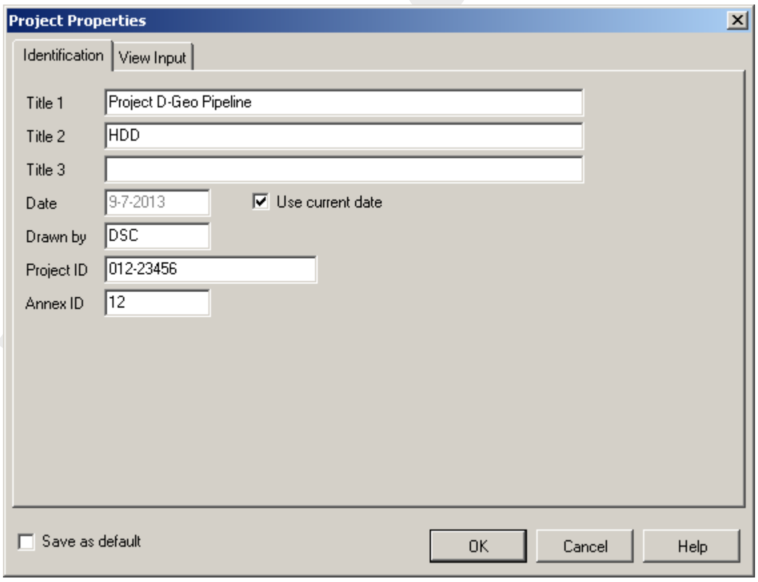


Figure 4.2: *Project Properties window, Identification tab*

Titles	Use *Title 1* to give the project a unique, easily recognizable name. *Title 2* and *Title 3* can be added to indicate specific characteristics of the calculation. The three titles will be included on printed output.
Date	The date entered here will be used on printouts and graphic plots for this project. Either mark the *Use current date* check-box to automatically use the current date on each printout, or enter a specific date.

Drawn by	Enter the name of the user performing the calculation or generating the printout.
Project ID	Enter a project identification number.
Annex ID	Specify the annex number of the printout.

Enable the check-box *Save as default* to use these settings every time D-GEO PIPELINE is started or a new project is created.

Project Properties – View Input

Use the *View Input* tab to define the appearance of the *View Input* window (section 2.2.3).

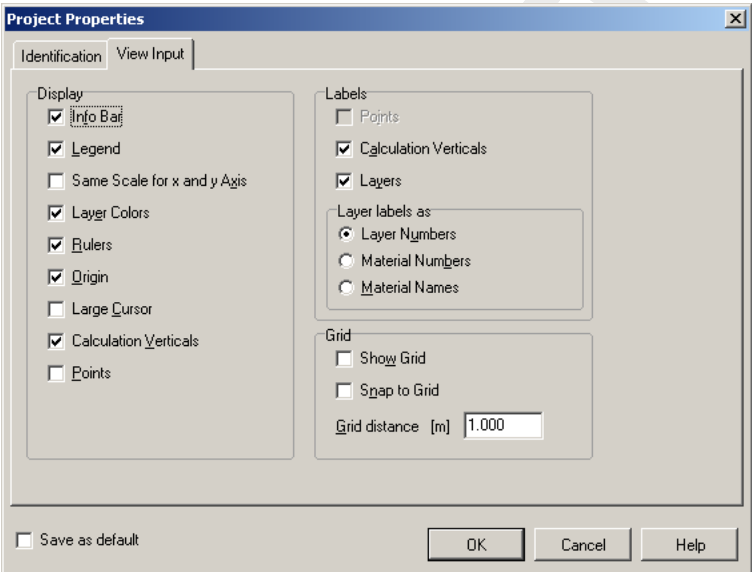


Figure 4.3: *Project Properties window, View Input tab*

Display	
Info Bar	Enable this check-box to display the information bar at the bottom of the *Outline View* window.
Legend	Enable this check-box to display the legend.
Same scale for x and y axis	Enable this check-box to display the x and y axis with the same scale.
Layer colors	Enable this check-box to display the layers in different colors.
Rulers	Enable this check-box to display the rulers.
Origin	Enable this check-box to draw a circle at the origin.
Large Cursor	Enable this check-box to use the large cursor instead of the small one.
Calculation Verticals	Enable this check-box to display the verticals.
Points	Enable this check-box to display the points.

Labels	
Points	Enable this check-box to display the point labels.
Calculation Verticals	Enable this check-box to display the vertical labels.
Layers	Enable this check-box to display the layer labels.

Layers labels as
This choice is available only if the *Layers* check-box of the *Labels* sub-window is marked. There are three ways to display the legend of the layers:

Layer Numbers	The legend displays one box for each layer. Each layer (and therefore each box) is displayed in a different standard color. Next to each box, the layer number and the material name are displayed, corresponding to the color and number of the layer in the adjacent *Geometry* window.
Material Numbers	The legend displays one box for each material. Each material (and therefore each box) is displayed in a different color which can be changed by the user (see section 7.3.3). Next to each box, the material number and name are displayed, corresponding to the color and number of the material in the adjacent *Geometry* window.
Material Names	The legend displays one box for each material. Each material (and therefore each box) is displayed in a different color which can be changed by the user (see section 7.3.3). Next to each box, only the material name is displayed, corresponding to the color and name of the material in the adjacent *Geometry* window.

Grid

Show grid	Enable this check-box to display the grid points.
Snap to Grid	Enable this check-box to ensure that objects align to the grid automatically when they are moved or positioned in a graph.
Grid distance	Enter the distance between two grid points.

Enable the *Save as default* check-box to use the current settings every time D-GEO PIPELINE is started.

4.1.3 View Input File

On the menu bar, click *Project* and then choose *View Input File* to display an overview of the input data.

The data will be displayed in the D-GEO PIPELINE main window. Click on the *Print Active Window* icon to print the file.

4.2 Soil menu

The *Soil* menu is used to enter the soil properties for the analysis. In the *Soil* menu, choose *Materials* to open the *Materials* input window in which the soil type properties can be defined. The Properties can either be imported directly from an MGeoBase database (*Database* tab), or be inputted manually (*Parameters* tab):

- ◇ Manual input of standard parameters (section 4.2.1);
- ◇ Manual input of settlement parameters acc. to Koppejan (section 4.2.2);
- ◇ Manual input of settlement parameters acc. to Isotache (section 4.2.3);
- ◇ Import from database (section 4.2.4).

4.2.1 Materials – Standard

If the *Use settlement* check-box in the *Model* window (section 4.1.1) is unmarked, the following window is displayed.

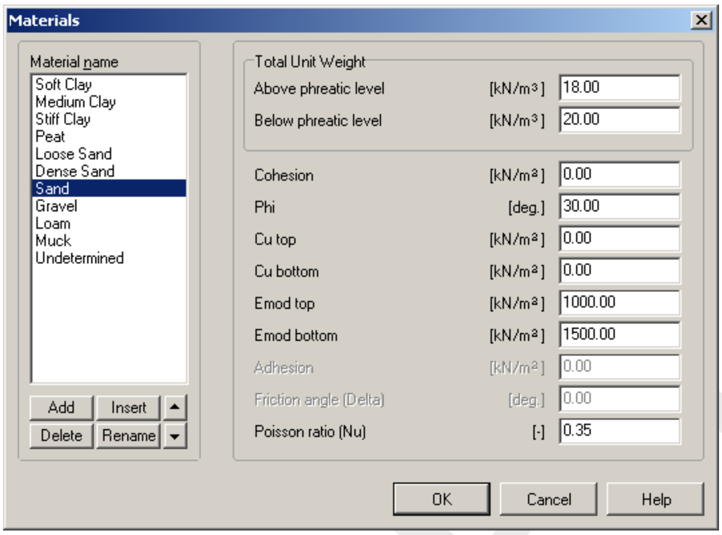


Figure 4.4: *Materials window, Parameters tab*

Total Unit Weight Above phreatic level	The unit weight of the unsaturated soil above the user-defined phreatic line.
Total Unit Weight Below phreatic level	The unit weight of the saturated soil below the user-defined phreatic line.
Cohesion	Cohesion of the soil.
Phi	Angle of internal friction of the soil.
Cu top	The apparent undrained cohesion c_u at the top of the layer.
Cu bottom	The apparent undrained cohesion c_u at the bottom of the layer.
Emod top	Young's modulus of the soil at the top of the layer.
Emod bottom	Young's modulus of the soil at the bottom of the layer.
Adhesion	Adhesion of the soil. The adhesion is only available if the *Construction in trench* or *Micro Tunneling* model have been selected in the *Model* window (section 4.1.1).
Friction angle (Delta)	Friction angle between soil and pipeline. The delta friction angle is only available if the *Construction in trench* or *Micro Tunneling* model have been selected in the *Model* window (section 4.1.1).
Poisson ratio (Nu)	Poisson ratio of the soil.

The Young's modulus E and the Poisson ratio ν are used to calculate G, the shear modulus:

$$G = \frac{E}{2(1+\nu)} \tag{4.1}$$

4.2.2 Materials – Settlement Koppejan

If the *Use settlement* check-box in the *Model* window (section 4.1.1) is marked and the *Koppejan* model is selected, D-GEO PIPELINE will calculate the settlements according to the Koppejan model. Therefore, the Koppejan parameters need to be put in as shown in Figure 4.5. For background information, refer to section 23.10.2.

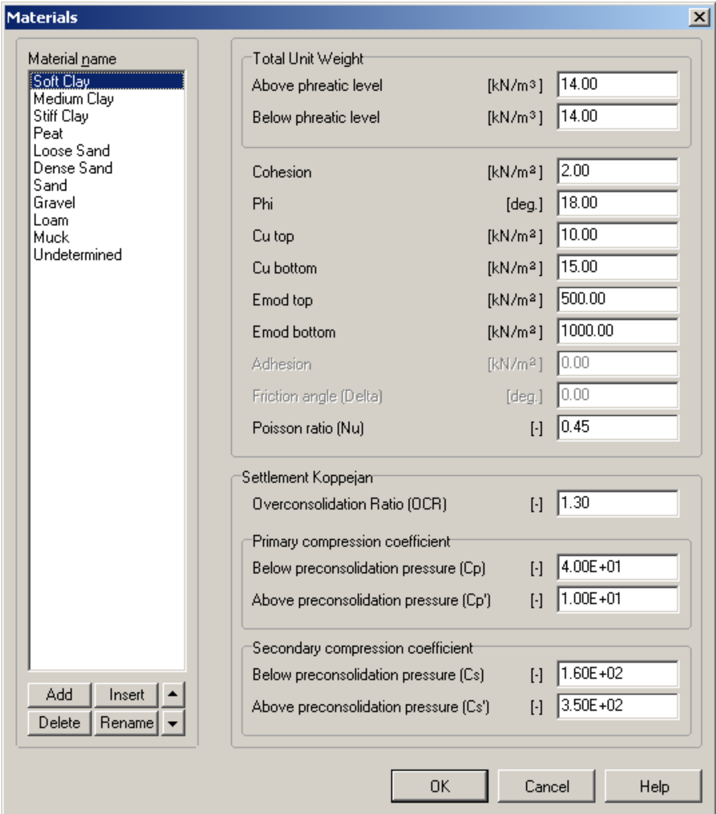


Figure 4.5: *Materials window, Parameters tab (Settlement acc. to Koppejan)*

Over-consolidation Ratio (OCR)	The Over-Consolidation Ratio (*OCR*) is defined as the ratio of pre-consolidation pressure and initial in situ vertical effective stress.
Primary compression coefficient below preconsolidation pressure (Cp)	The primary compression coefficient C_{p} is used to calculate the primary settlement.
Primary compression coefficient above preconsolidation pressure (Cp')	The primary compression coefficient C_{p}' is used to calculate the primary settlement.
Secondary compression coefficient below preconsolidation pressure (Cs)	The secondary compression coefficient C_{s} is used to calculate the secondary (time dependent) settlement.
Secondary compression coefficient above preconsolidation pressure (Cs')	The secondary compression coefficient C_{s}' is used to calculate the secondary (time dependent) settlement.

4.2.3 Materials – Settlement Isotache

If the *Use settlement* check-box in the *Model* window [section 4.1.1] is unmarked and the *Isotache* model is selected, D-GEO PIPELINE will calculate the settlements according to the Isotache model. Therefore, the Isotache parameters need to be put in as shown in Figure 4.6. For background information, see section 23.10.1.

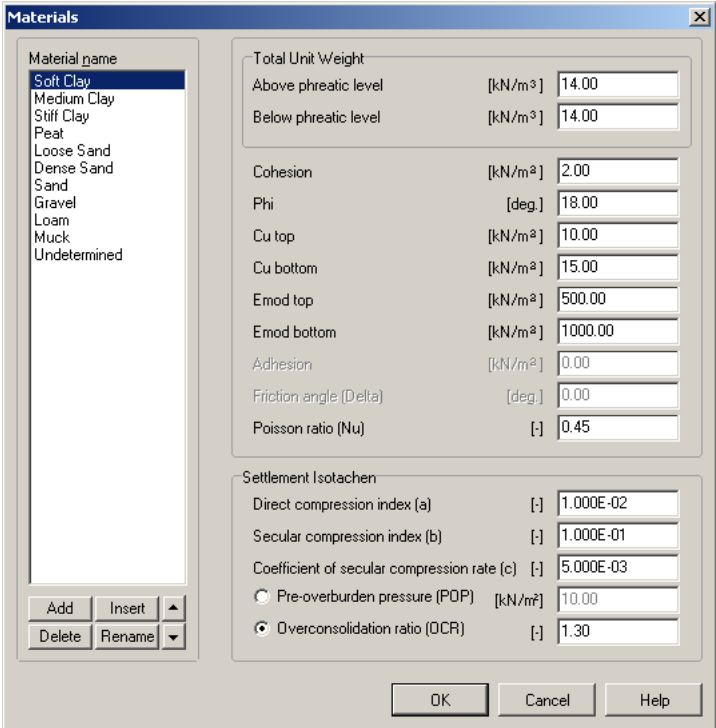


Figure 4.6: *Materials window, Parameters tab (Settlement acc. to Isotache)*

Direct compression index (a)	The direct compression index a relates natural strain during re-compression or swell to the change of vertical effective stress.
Secular compression index (b)	The secular compression index b relates natural strain during virgin loading to the change of vertical effective stress.
Coefficient of secular compression rate (c)	The coefficient of secular compression rate c relates natural strain to the change of time. A zero value indicates non-creeping soil.
Pre-overburden pressure (POP)	The Pre-Overburden Pressure (POP) is defined as the pre-consolidation pressure minus the initial in situ vertical effective stress.
Overconsolidation ratio (OCR)	The Over-Consolidation Ratio (OCR) is defined as the ratio of pre-consolidation pressure and initial in situ vertical effective stress.

4.2.4 Materials – Database

The *Database* tab in the *Materials* window is only available if a location of an MGeobase database was specified in the *Locations* tab of the *Program Options* window (section 3.2.3).

Select the *Database* tab in the *Materials* window to see the available soil types. Select a soil type, and use the *Import* button to import the soil type with associated properties.

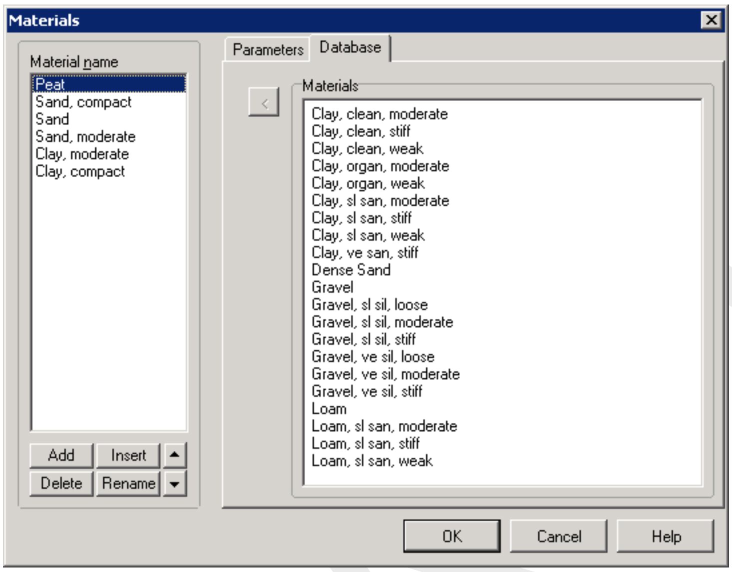


Figure 4.7: *Materials window, Database tab*

4.3 Geometry menu

On the menu bar, click *Geometry* to display the menu options. These options are explained in the following sections.

- ◇ *New* (section 4.3.1). Start creating a new geometry manually.
- ◇ *New Wizard* (section 4.3.2). Create a new geometry using a wizard.
- ◇ *Import* (section 4.3.3). Import a geometry file in the D-series exchange format.
- ◇ *Import geometry from database* (section 4.3.4). Import geometry from a database.
- ◇ *Export* (section 4.3.5). Save a geometry file for exchange with other Deltares Systems programs.
- ◇ *Export as Plaxis/Dos* (section 4.3.6). Save a geometry file in a different format.
- ◇ *Limits* (section 4.3.7). Set the range of the horizontal coordinates.
- ◇ *Points* (section 4.3.8). Add or manipulate points.
- ◇ *Import PL-line* (section 4.3.9). Import a PL-line file in the D-Series exchange format.
- ◇ *PL-lines* (section 4.3.10). Add or manipulate piezometric level lines.
- ◇ *Phreatic line* (section 4.3.11). Define phreatic level lines.
- ◇ *Layers* (section 4.3.12). Define or modify layer boundaries and corresponding soil types.
- ◇ *PL-lines per layer* (section 4.3.13). Select the piezometric level line at the bottom and top of each layer.
- ◇ *Check geometry* (section 4.3.14). Check the validity of the geometry.

4.3.1 New

Select this option to display the *View Input (Geometry)* window, showing only the geometry limits (with their default values) of the geometry. It is possible to now start modeling the geometry (for more information on this subject, see chapter 7). However, it is possible to create a new geometry faster and easier using the *Geometry Wizard* (section 4.3.2). This wizard involves a step-by-step process for creating geometry.

4.3.2 New Wizard

The *New Wizard* is usually the fastest and easiest way to start creating new geometry. The wizard uses predefined shapes and soil types.

To use the geometry wizard, click the *Geometry* menu and choose *New Wizard*. This wizard provides the following step-by-step guidance:

- ◇ Basic layout
- ◇ Shape selection
- ◇ Shape definition
- ◇ Material types
- ◇ Summary

New Wizard – Basic Layout

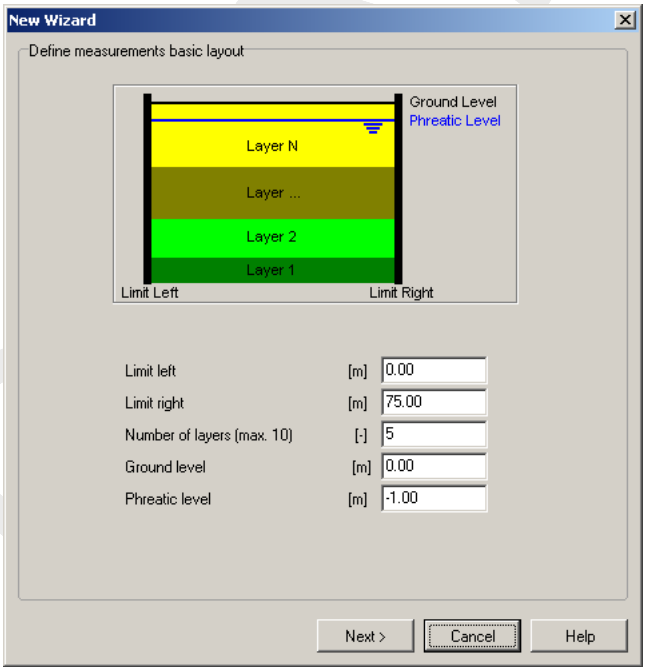


Figure 4.8: *New Wizard window (Basic Layout)*

In the *Basic Layout* window (Figure 4.8), the basic framework within which the project is defined can be entered. The graphic at the top of the window explains the required input. When satisfied with the input, just click the *Next* button to display the next input screen.

New Wizard – Shape Selection

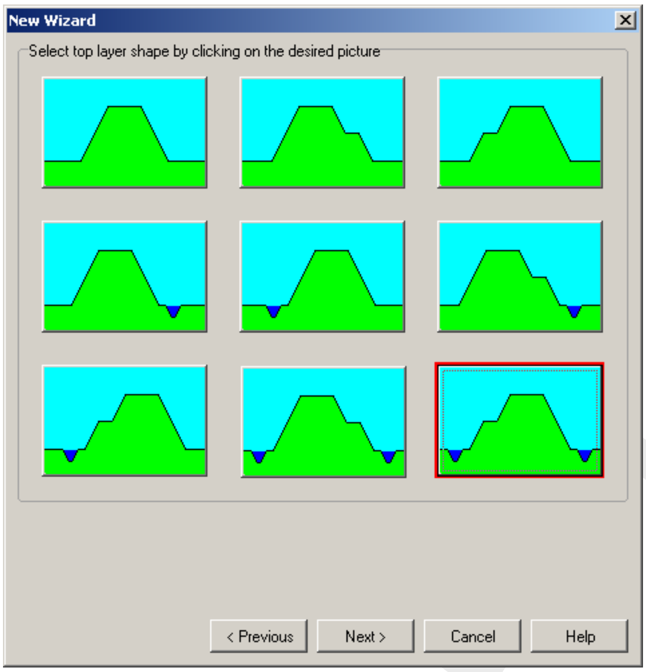


Figure 4.9: *New Wizard window (Top Layer Shape)*

In the *Top Layer Shape* window (Figure 4.9), one of nine default top-layer shapes can be selected. A red frame indicates the selected shape. Click the *Previous* button to return to the *Basic Layout* screen, or the *Next* button to display the next input screen with shape-specific input data.

New Wizard – Shape definition

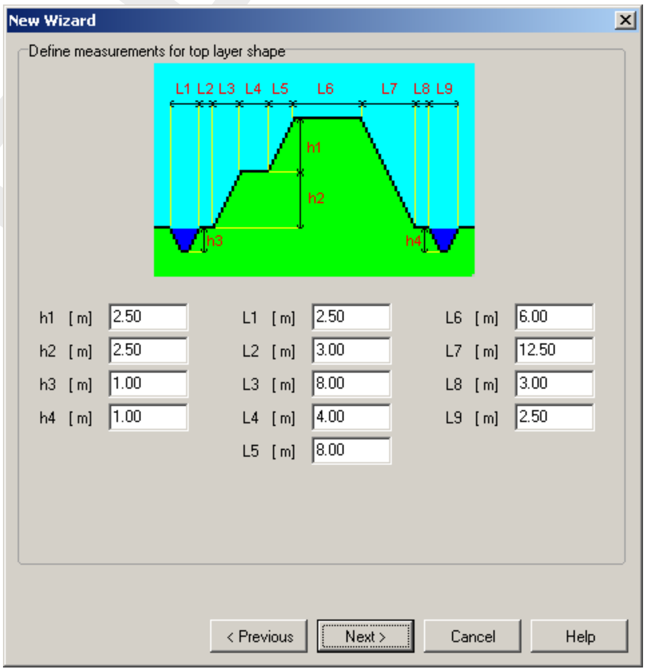


Figure 4.10: *New Wizard window (Top Layer Specification)*

The *Top Layer Specification* window (Figure 4.10) enables to specify the sizes of the selected top layer shape.

New Wizard – Material Types

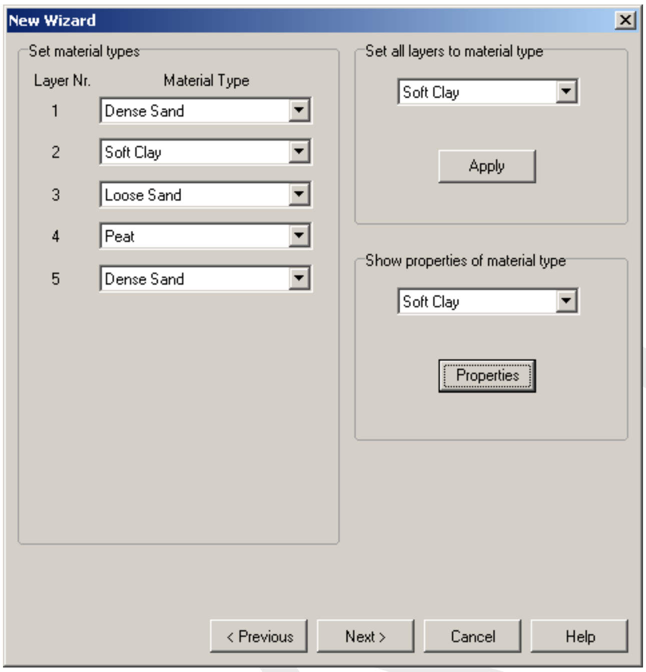


Figure 4.11: *New Wizard window (Material Types)*

In the *Material Types* window (Figure 4.11), the materials used for the layers in the project can be specified. The number of layers was defined in the first screen (Basic Layout). The materials that can be chosen from are predefined (see Table 4.10).

Table 4.10: *Unsaturated and saturated weight of the predefined materials*

Material type	**Unsaturated weight [kN/m^3]**	**Saturated weight [kN/m^3]**
Soft Clay	14	14
Medium Clay	17	17
Stiff Clay	19	19
Loose Sand	17	19
Dense Sand	19	21
Loose Aggregate	17	19
Dense Aggregate	19	21
Peat	12	12

The materials for each layer can be selected individually (using the selection boxes at the left-hand side of the screen) or one material for each layer at once can be selected (using the selection box at the top right of the screen). The parameters of each material can also be reviewed.

New Wizard – Summary

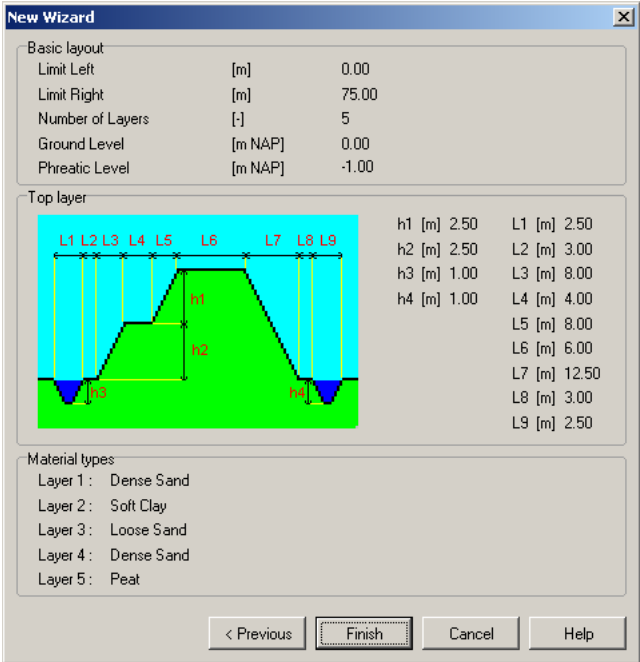


Figure 4.12: *New Wizard window (Summary)*

The *Summary* window (Figure 4.12) displays an overview of the data entered in the previous wizard screens. If necessary, click *Previous* to go back to any screen and change the data as required. Clicking *Finish* will confirm the input and display the geometry in the *View Input Geometry* window. In this window, the geometry can be edited or completed graphically as described in chapter 7. Of course, the *Geometry* menu options can also be used for this purpose (section 4.3).

4.3.3 Import

This option displays a standard file dialog in which an existing geometry can be selected stored in a geometry file, or in an existing input file for D-GEO STABILITY (formerly known as MStab), D-SETTLEMENT (formerly known as MSettle), MSeep and D-SHEET PILING (formerly known as MSheet). For a full description of these programs and how to obtain them, visit www.deltaressystems.com.

When selecting the geometry, it is imported into the current project, replacing the current geometry. The imported geometry is displayed in the *View Input (Geometry)* window. It is also possible to use this option to analyze the settled geometry at different stages, as all other input is retained.

4.3.4 Import geometry from database

To be able to import a geometry from a database, this option has to be provided with the purchased version of D-GEO PIPELINE.

To import a geometry from a database do the following:

◇ Click *Import* from *Database* in the *Geometry* menu.
◇ The *Select Geometry* dialog will appear.

Again, the imported geometry will replace the current one and will be displayed in the *View Input (Geometry)* window.

Note: This option is only available when the correct database directory has been specified using the *Locations* tab in the *Program Options* menu (see section 3.2.3). For more information on MGeoBase, visit www.deltaressystems.com.

4.3.5 Export

This option displays a standard *Save As* dialog that enables the user to choose a directory, a file name and a format in which to save the current geometry to a file. The file will be saved in the standard geometry format for the Deltares Systems programs (*.geo). Files in this format can be used in a multitude of Deltares Systems programs, such as D-GEO STABILITY (formerly known as MStab), D-SETTLEMENT (formerly known as MSettle), MSeep and D-SHEET PILING (formerly known as MSheet). For a full description of these programs and how to obtain them, visit www.deltaressystems.com.

4.3.6 Export as Plaxis/DOS

This option displays the *Save As Plaxis/DOS* dialog that enables the user to choose a directory and a file name in which to save the current geometry. The file will be saved using the old DOS-style geometry format for the Deltares Systems programs. Files in this format can be used by the finite element program Plaxis and in old DOS-based versions of Deltares Systems programs such as D-GEO STABILITY (DOS) and MZet (DOS).

Saving files of this type will only succeed, however, if the stringent demands imposed by the old DOS style are satisfied:

- ◇ number of layers ≤ 20
- ◇ number of PL-lines ≤ 20
- ◇ number of lines per boundary < 50
- ◇ total number of points ≤ 500

To be able to differentiate between an old DOS-style file and a normal geometry file, the file dialog that prompts for a new file name for the old DOS-style geometry file suggests a default file name, prefixing the current name with a ‘D’.

4.3.7 Limits

Use this option to edit the geometry limits.

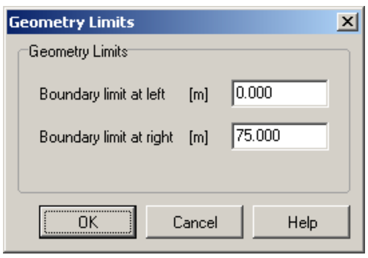


Figure 4.13: *Geometry Limits window*

A limit is a vertical boundary defining the ‘end’ at either the left or right side of the geometry. It is defined by an X-coordinate only.

Note: This is the only type of element that cannot be deleted. Moreover, the values entered here are ignored if they resulted in an invalid geometry.

4.3.8 Points

Use this option to add or edit points that can be used as part of layer boundaries or PL-lines. A point is a basic geometry element defined by its coordinates. Since the geometry is restricted to two dimensions, it is allowed to define an L and Z co-ordinates only.

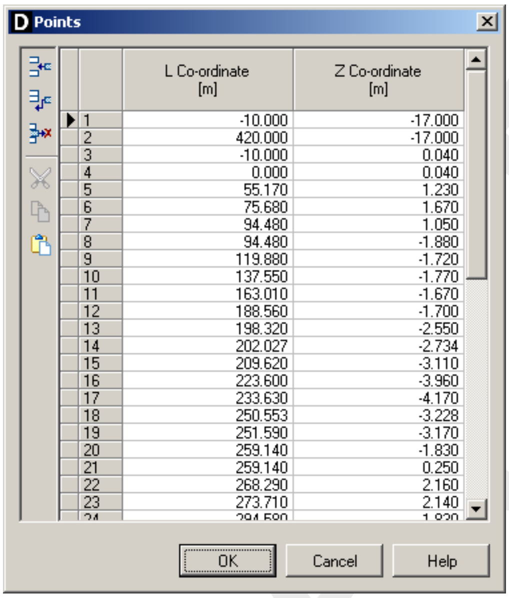


Figure 4.14: *Points window*

L Co-ordinate	Projection of the horizontal co-ordinate along the pipeline trajectory.
Z Co-ordinate	Vertical co-ordinate.

Note: When a point is to be deleted, the system will check whether the point is used as part of a PL-line or layer boundary. If so, a message will be displayed.

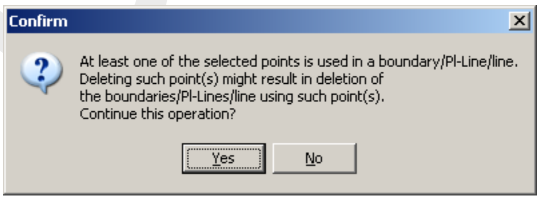


Figure 4.15: *Confirm window for deleting used points*

When *Yes* is clicked, all layer boundaries and/or PL-lines using the point will also be deleted.

Every change made using this window (Figure 4.14) will only be displayed in the underlying *View Input (Geometry)* window after closing this window using the *OK* button. When this button is clicked, a validity check is performed on the geometry. Any errors encountered during this check are displayed in a separate window. These errors must be corrected before

closing this window by clicking the *OK* button. Of course, it is always possible to close the window using the *Cancel* button, but this will discard all changes.

4.3.9 Import PL-line

This option displays a standard file dialog in which an existing PL-line, created with the program WATEX and stored in a PL-line file (*.mpl), can be selected.

WATEX (Deltares, 2004) is a reliable prediction tool to assess the pore pressure behavior. It consists of transient analytical solutions, put together by the conditions of continuity of head and discharge. The user specifies a number of locations, where the pore pressure response is required.

When a PL-line file is selected, the *Options for Import of Pl-line* window (Figure 4.16) is displayed. When clicking the *OK* button, then the PL-line is added to the current PL-lines in the project.

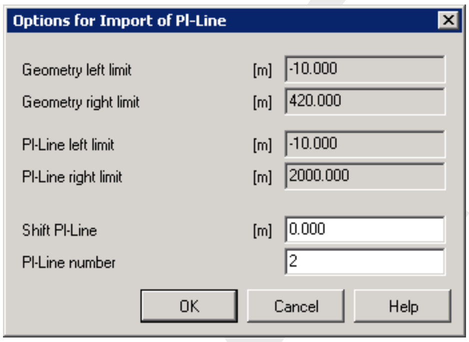


Figure 4.16: *Options for Import of PL-line window*

4.3.10 PL-Lines

Use this option to add or edit Piezometric Level lines (PL-lines) to be used in the geometry. A PL-line represents the hydraulic head Hydraulic head of the water in the pores of the soil. A PL-line can be defined for the top and bottom of each soil layer (see section 4.3.13). The bottom soil layer is assumed to be infinitely thick. Here, therefore, only one PL-line is necessary for the top of that layer. Pore pressures in this layer are hydrostatic with increasing depth.

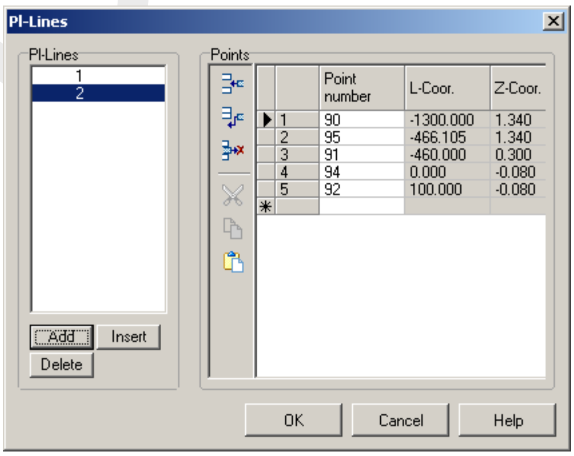


Figure 4.17: *PL-Lines window*

In the lower part of the window, the buttons *Add*, *Insert* and *Delete* PL-lines can be used. The selection box on the left can be used to navigate between PL-lines that have already been defined. Use the table to add/edit the points identifying the PL-lines. It is only possible to select points that are not attached to layer boundaries (section 4.3.12).

Note: It is only possible to manipulate the *Point number* column – that is, the coordinate columns are purely for informative purposes. To edit the coordinates of the points, choose the *Points* option from the *Geometry* menu (see section 4.3.8).

Every change made using this window will only be displayed in the underlying *View Input (Geometry)* window after closing this window using the *OK* button. When clicking this button, a validity check is performed on the geometry. Any errors encountered during this check are displayed in a separate window. These errors must be corrected before closing this window using the *OK* button. Of course, it is always possible to close the window using the *Cancel* button, but this will discard all your changes.

4.3.11 Phreatic Line

Use this option to select the PL-line that acts as a phreatic line. The phreatic line (or groundwater level) is used to mark the border between dry and wet soil.

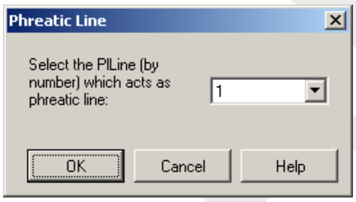


Figure 4.18: *Phreatic Line window*

Select the appropriate line number from the drop-down list and click the *OK* button.

Note: At least one PL-line has to be defined to be able to pick a phreatic line from the drop-down list.

4.3.12 Layers

This option enables to add or edit layers to be used in the geometry. A layer is defined by its boundaries and its material. Use the *Boundaries* tab to define the boundaries for all layers by choosing the points that identify each boundary.

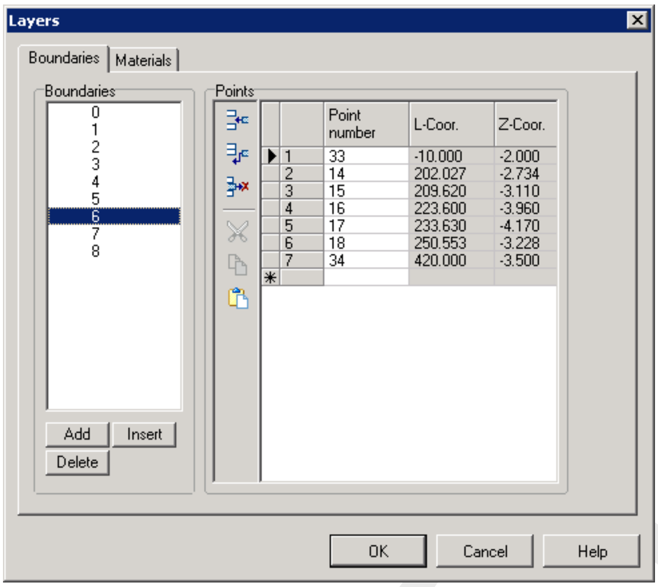


Figure 4.19: *Layers window, Boundaries tab*

On the left-hand side of the window, it is possible to add, insert, delete or select a boundary. In the table on the right, it is possible to modify or add the points that identify the selected boundary.

Note: It is only possible to select points that are not attached to PL-lines (section 4.3.10).

Note: It is only possible to manipulate the *Point number* column, because the coordinate columns are purely for informative purposes. To manipulate the coordinates of the points, choose the *Points* option in the *Geometry* menu (see section 4.3.8).

Note: When inserting or adding a boundary, all points of the previous boundary (if this exists) are automatically copied. By default, the material of a new layer is set equal to the material of the existing layer just beneath it.

The *Materials* tab enables to assign materials to the layers.

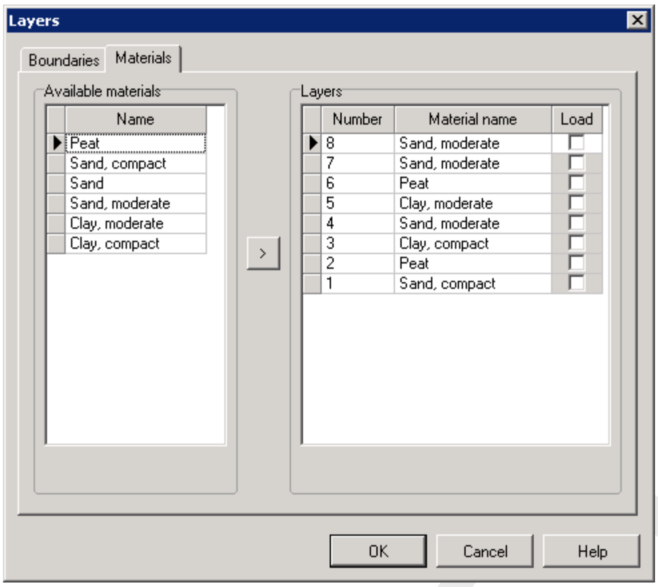


Figure 4.20: *Layers window, Materials tab*

On the left of the screen, a list containing all defined materials (see the *Materials* option in the *Soil* menu in section 4.2.1) is displayed. On the right, a list of all defined layers together with their assigned materials (if available) is displayed.

To assign a material to a layer, first select that layer on the right of the window. Then select the required material on the left of the window. Finally, click the *Assign* button .

In case of settlement calculation using the Koppejan or the Isotache model (section 4.1.1), the loading is defined by marking the *Load* check-box of one or several layers. D-GEO PIPELINE assumes that those layers are non-uniform loads.

Every change made using this window will only be displayed in the underlying *View Input (Geometry)* window after closing this window by clicking the *OK* button. When clicking this button, a validity check is performed on the geometry. If errors are encountered, a dialog window asks if auto-correction should be tried. Remaining errors are reported and can be corrected manually. The error correction is confirmed by clicking the *OK* button and discarded by clicking the *Cancel* button.

4.3.13 PL-lines per Layer

Use this option to define the top and bottom PL-lines for the defined layers. The PL-lines represent the pore pressure in a soil layer. For each soil layer (except the deepest layer), two PL-line numbers can be entered – one that corresponds to the top of the soil layer, and one that corresponds to the bottom. Therefore, different PL-lines can be defined for the top and bottom of each soil layer. To do this, select the appropriate *PL-line at top / PL-line at bottom* field and enter the appropriate number.

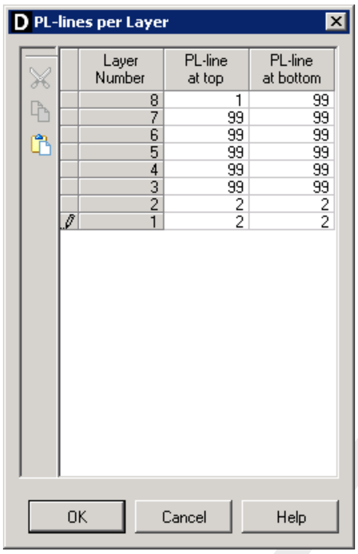


Figure 4.21: *PL-line per Layer window*

Note: For the deepest soil layer, no second PL-line number is required. For this layer a hydrostatic increase of the pore pressure is automatically assumed from the pore pressure at the top of the layer downwards.

The following values can be used as PL-line numbers (N):

$0 < N < 99$	The number corresponds to one of the PL-lines defined during the geometry input. Capillary water pressures are not used – that is, if a negative water pressure is calculated for a point above the phreatic line, the water pressure in that point is defined as 0.
N = 0	Each point within the layer has a water pressure equal to 0 (define 0 for PL-line at top of layer).
N = 99	It is possible to have a number of overlying soil layers with a non-hydrostatic pore pressure (for example, a number of layers consisting of cohesive soil). In this case, a large number of PL-lines would have to be calculated, one or two for each layer. To avoid this, D-series software is able to interpolate across layer boundaries. For layers with a non-hydrostatic pore pressure, 99 can be entered as the PL-line number. For this layer, the interpolation will take place between the PL-line belonging to the first soil layer above with a real PL-line number, and the PL-line belonging to the first soil layer below with a real PL-line number. The first and the last soil layer must therefore always have a real PL-line number. **Note:** A real PL-line number is not equal to 99.

Water pressures above the phreatic line are set to zero. An example using two different PL-lines is given in Figure 4.22 showing how the pore pressure varies in the vertical.

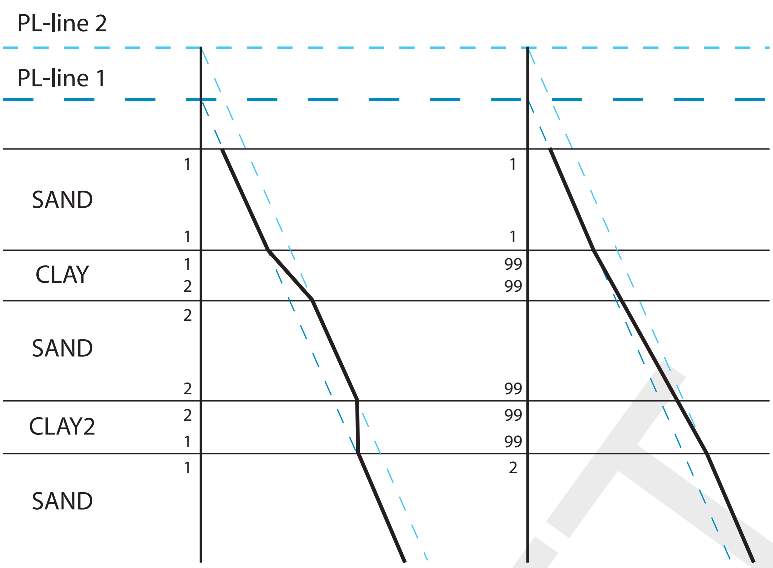


Figure 4.22: *PL-lines and vertical pressure distribution*

When clicking the *OK* button, the program performs a validity check on the geometry. Any errors encountered during this check are reported. A dialog window enables to disregard or correct the errors. The error correction is confirmed by clicking the *OK* button and discarded by clicking the *Cancel* button.

4.3.14 Check Geometry

When this option is selected, the program checks the validity of the geometry (section 7.2) with respect to the requirements. If the geometry complies with all the requirements, a message will confirm this.

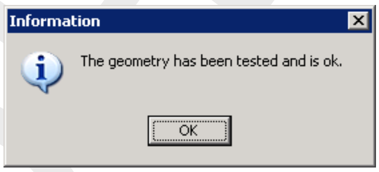


Figure 4.23: *Information window to confirm a valid geometry*

If any errors are encountered during this check, they are displayed in a separate window.

4.4 GeoObjects menu

4.4.1 Boundaries Selection

Click *GeoObjects* on the menu bar and select *Boundaries Selection* to define the boundaries between compressible top layers and under laying non-compressible layers and the boundary between drained (i.e. cohesive) top layers and under laying non-cohesive (i.e. undrained) layers (Figure 4.24). This is done by choosing the layer number of the underlying layer.

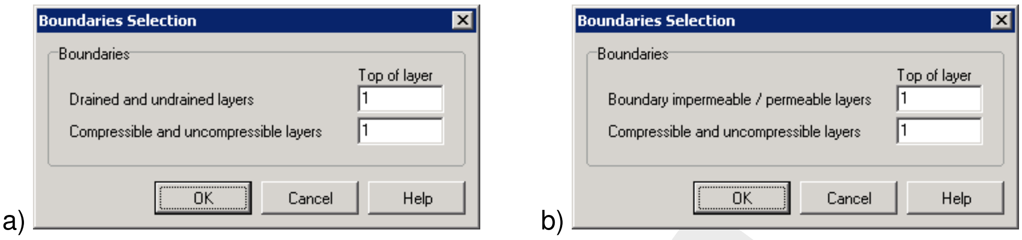


Figure 4.24: *Boundaries Selection window for (a) HDD/Micro-tunneling and (b) for Trenching*

The boundary between compressible and non-compressible layers is drawn as a blue bold line and the boundary between drained and undrained layers (i.e. impermeable and permeable layers) is drawn as a black bold line in the *Input* tab of the *View Input* window (see section 2.2.3).

4.4.2 Calculation Verticals

Click *GeoObjects* on the menu bar and select *Calculation Verticals* to define the L-coordinate for each vertical. D-GEO PIPELINE will perform calculations along each of these verticals. At least one vertical is necessary to perform any calculation.

The verticals must be placed within the left and right project limits.For an accurate impression of the change in drilling fluid pressure along the pipeline, it is advised to use at least 10-15 verticals.

It is possible to generate a number of verticals using the *Auto generation of L co-ordinates* option and clicking the *Generate* button 

. D-GEO PIPELINE will generate verticals between the *First* and *Last* co-ordinates with a fixed width, entered in the *Interval* field.

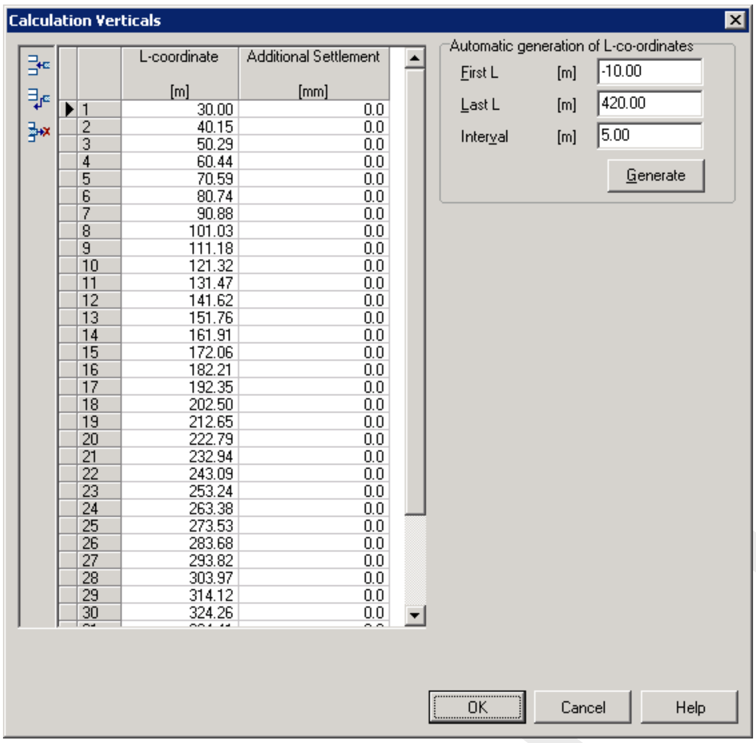


***Figure 4.25:** Calculation Verticals window*

L-coordinate	Defines the locations in geometry in the L direction where the calculations are performed. L represents distance along the pipe line projection in the horizontal plane incremented with the entry coordinate. The L-coordinate value must increase with each vertical.
Additional Settlement	Enter an additional settlement for the selected vertical. This settlement will be added to the calculated settlement (according to Koppejan or Isotache) in the table of the *Deformation* section of the *Report* window (section 6.2.2).
First L	L co-ordinate of the starting point of generated verticals.
Last L	L co-ordinate of the ending point of generated verticals.
Interval	Interval between generated verticals.
Generate	Click this button to generate automatically verticals from *First* to *Last L* with the mentioned *Interval*.

4.5 Loads menu

4.5.1 Traffic Loads

On the menu bar, click *Loads* and then choose *Traffic Loads* to open the corresponding input window in which the positions of traffic loads can be defined. Traffic loads will have an influence on the calculated soil load stress, only for the calculation verticals situated

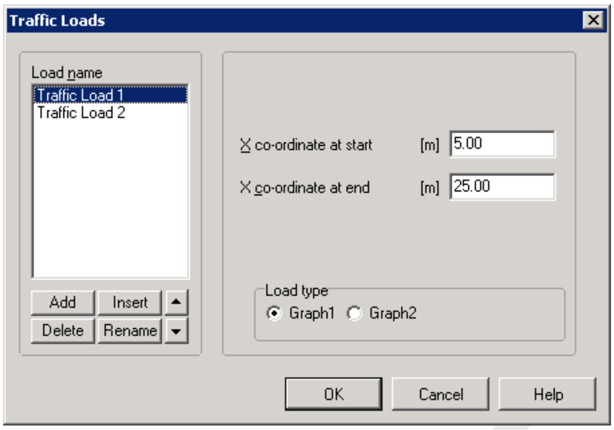


Figure 4.26: *Traffic Loads window*

X co-ordinate at start	Enter the X co-ordinate of the starting point of the selected traffic load.
X co-ordinate at end	Enter the X co-ordinate of the ending point of the selected traffic load.
Load type	According to article C.5.1 of NEN 3650-1 (NEN, 2012a), two load models are considered, depending on the type of road: ◇ For dual carriageways and regional roads, Graph I (i.e. 'Load Model 3' of European standard EN NEN-1991-2) is assumed; ◇ For other roads, Graph II (i.e. 'Fatigue Load Model 2, Lorry 4' of European standard EN NEN-1991-2) is assumed. This load model covers the 'set of frequent lorries' which can occur on European roads, such as described in EN NEN-1991-2, with exception of the special transports). For more information, refer to section 23.14.

4.6 Pipe menu

4.6.1 Pipeline Configuration

On the menu bar, click *Pipe* and then choose *Pipeline Configuration* to open the corresponding input window in which the geometric characteristics of the pipeline can be defined. The *Pipeline Configuration* window displayed depends on the selected model.

4.6.1.1 Pipeline Configuration for HDD

If the *Horizontal directional drilling* option in the *Model* window (section 4.1.1) is selected, the *Pipeline Configuration* window shown in Figure 4.27 is displayed.

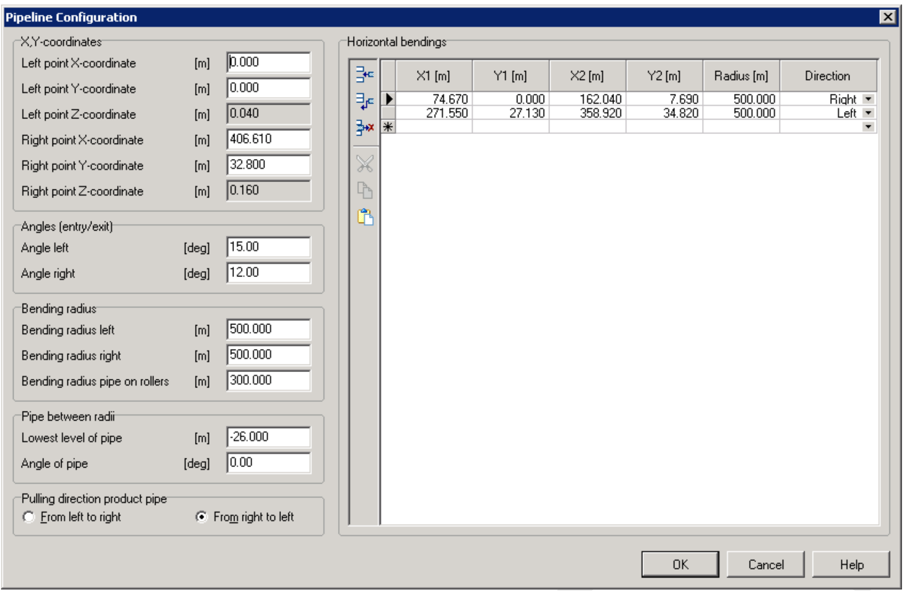


Figure 4.27: *Pipeline Configuration window (for HDD)*

Left point X-coordinate	X-coordinate of the left point which corresponds whether the entry or the exit point of the pipeline (called X_{left} in Figure 4.28).
Left point Y-coordinate	Y-coordinate of the left point which corresponds whether the entry or the exit point of the pipeline (called Y_{left} in Figure 4.28).
Left point Z-coordinate	Z-coordinate (i.e. vertical level) of the left point which corresponds whether the entry or the exit point of the pipeline (called Z_{left} in Figure 4.28). This coordinate corresponds with the surface level for $X = X_{\text{left}}$ and is automatically calculated by the program.
Right point X-coordinate	X-coordinate of the right point which corresponds whether the entry or the exit point of the pipeline (called X_{right} in Figure 4.28).
Right point Y-coordinate	Y-coordinate of the right point which corresponds whether the entry or the exit point of the pipeline (called Y_{right} in Figure 4.28).
Right point Z-coordinate	Z-coordinate of the right point which corresponds whether the entry or the exit point of the pipeline (called Z_{right} in Figure 4.28). This coordinate corresponds with the surface level for $X = X_{\text{right}}$ and is automatically calculated by the program.
Angle left	Left angle of the pipe (called φ_{left} in Figure 4.28).
Angle right	Right angle of the pipe (called φ_{right} in Figure 4.28).
Bending radius left	Bending radius of the pipe at the left side (called R_{left} in Figure 4.28).
Bending radius right	Bending radius of the pipe at the right side (called R_{right} in Figure 4.28).
Bending radius pipe on rollers	Only available for HDD model. Bending radius on the pipe roller, depending on the diameter of the product pipe (called R_{rollers} in Figure 4.28).
Lowest level of pipe	Lowest level of the pipe (called Z_{lowest} in Figure 4.28).
Angle of pipe	Horizontal angle of the lowest straight part of the configuration.
Pulling direction product pipe	The pulling force at characteristics points can be calculated for a pulling direction *From left to right* (i.e. the left point is the entry point) and *From right to left* (i.e. the right point is the entry point).
X1	X co-ordinate of the beginning point of the horizontal bending (see Figure 4.28).

Y1	Y co-ordinate of the beginning point of the horizontal bending (see Figure 4.28).
X2	X co-ordinate of the ending point of the horizontal bending (see Figure 4.28).
Y2	Y co-ordinate of the ending point of the horizontal bending (see Figure 4.28).
Radius	Radius of the horizontal bending (called R_{bending} in Figure 4.28).
Direction	From the drop-down menu, select the direction of the horizontal bending (*Left* or *Right*). For example, the horizontal bending of Figure 4.28 has a left direction.

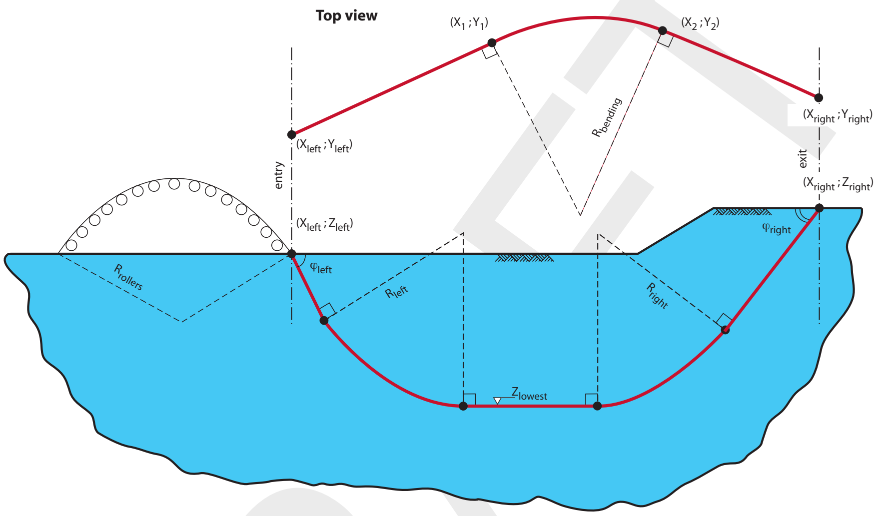


Figure 4.28: *Schematization of the pipeline (HDD)*

Needless to say, the coordinates must be defined properly. For example, the X-coordinate of the right point must have a higher value than the coordinate of the left point.

The pipeline configuration is given at the center of the pipe. It is assumed that during all drilling stages (pilot, drill and pullback) the defined center of the pipeline is the same. From each pipe, the diameter of the pipe as well as the diameter of the hole must be known.

4.6.1.2 Pipeline Configuration for Micro tunneling

If the *Micro tunneling* option in the *Model* window (section 4.1.1) is selected, the *Pipeline Configuration* window shown in Figure 4.29 is displayed.

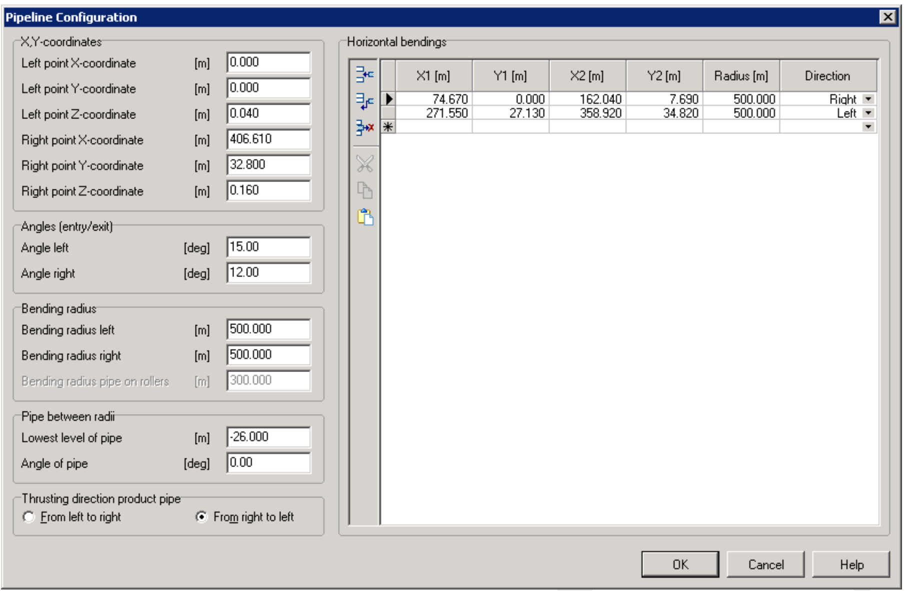


Figure 4.29: *Pipeline Configuration window (for Micro tunneling)*

Thrusting direction product pipe	The thrusting force can be calculated for a pulling direction *From left to right* (i.e. the left point is the entry point) and *From right to left* (i.e. the right point is the entry point).
Refer to the table above for the definition of the other parameters	

Note: To model a horizontal micro-tunneling, enter an *Angle left* and an *Angle right* of 0.

4.6.1.3 Pipeline Configuration for Construction in trench

If the *Construction in trench* option in the *Model* window (section 4.1.1) is selected, the *Pipeline Configuration* window shown in Figure 4.30 is displayed. Different pipe materials can be defined along the pipeline.

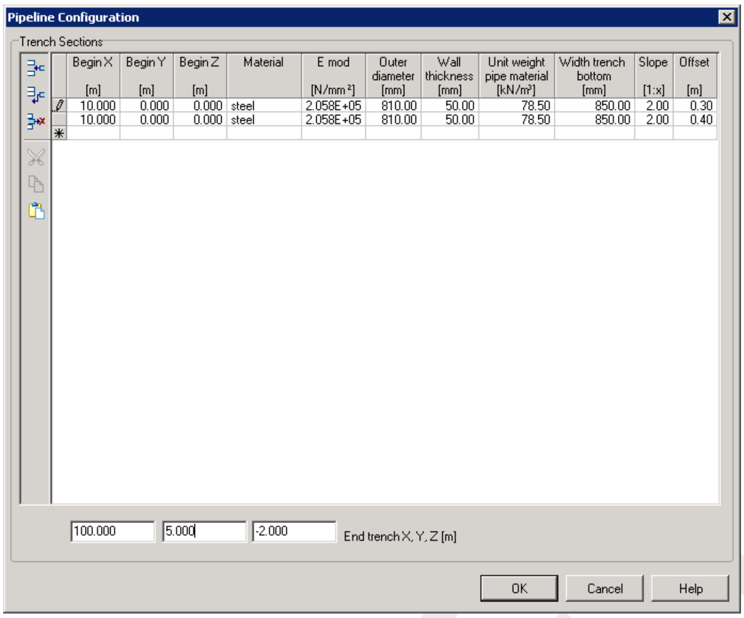
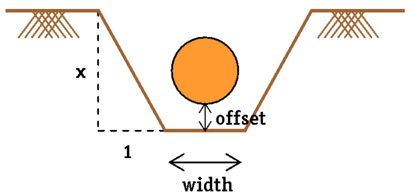


Figure 4.30: *Pipeline Configuration window (Construction in trench)*

Begin X	X co-ordinate of the begin point of the trench section.
Begin Y	Y co-ordinate of the begin point of the trench section.
Begin Z	Z co-ordinate of the begin point of the trench section.
Material quality	Description of the material quality. The data in this field is used in the report.
Outer diameter	Outer diameter of the pipe in mm.
Wall thickness	Wall thickness of the pipe in mm.
Unit weight pipe material	Unit weight of the pipe material.
Width trench bottom	Width of the trench bottom.
Slope 1:x	Slope of the trench.
Offset	Distance between the bottom of the trench and the bottom of the pipeline.



End trench X	X co-ordinate of the end point of the last trench section.
End trench Y	Y co-ordinate of the end point of the last trench section.
End trench Z	Z co-ordinate of the end point of the last trench section.

4.6.1.4 Pipeline Configuration for Direct Pipe

If the *Direct Pipe* option in the *Model* window (section 4.1.1) is selected, the *Pipeline Configuration* window shown in Figure 4.32 is displayed. For Direct pipe, a borepath with two bends and three straight sections is assumed. The path is defined according to Figure 4.31.

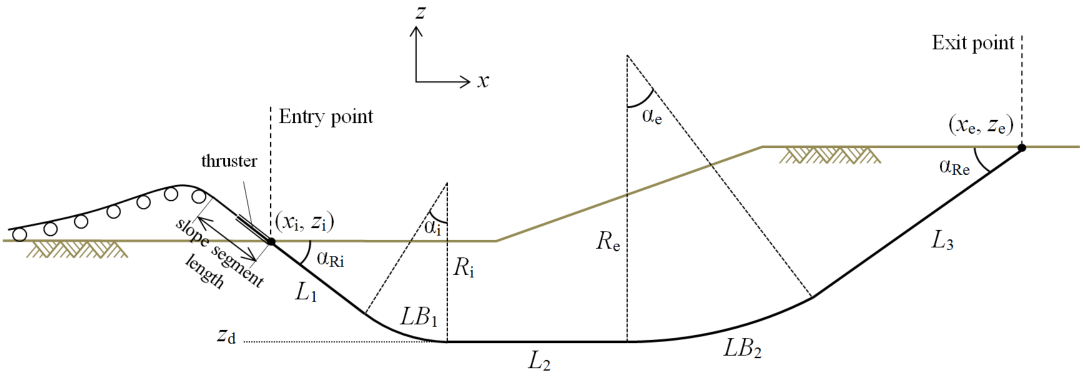


Figure 4.31: *Bore-path definition for Direct Pipe method*

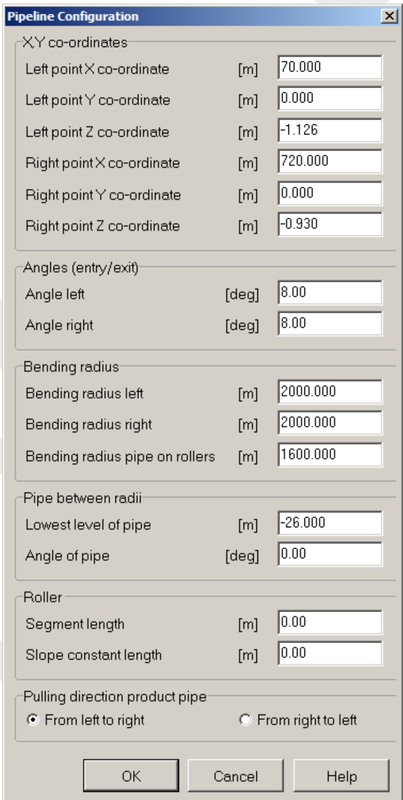


Figure 4.32: *Pipeline Configuration window (Direct Pipe)*

Left point X-coordinate	X-coordinate of the left point which corresponds whether the entry or the exit point of the pipeline (called x_i in Figure 4.31).
Left point Y-coordinate	Y-coordinate of the left point which corresponds whether the entry or the exit point of the pipeline.

Left point Z-coordinate	Z-coordinate (i.e. vertical level) of the left point which corresponds whether the entry or the exit point of the pipeline (called z_i in Figure 4.31).
Right point X-coordinate	X-coordinate of the right point which corresponds whether the entry or the exit point of the pipeline (called x_e in Figure 4.31).
Right point Y-coordinate	Y-coordinate of the right point which corresponds whether the entry or the exit point of the pipeline.
Right point Z-coordinate	Z-coordinate of the right point which corresponds whether the entry or the exit point of the pipeline (called z_e in Figure 4.31).
Angle left	Left angle of the pipe (called αRi in Figure 4.31).
Angle right	Right angle of the pipe (called αRe in Figure 4.31).
Bending radius left	Bending radius of the pipe at the left side (called R_i in Figure 4.31).
Bending radius right	Bending radius of the pipe at the right side (called R_e in Figure 4.31).
Bending radius pipe on rollers	Only available for HDD model. Bending radius on the pipe roller, depending on the diameter of the product pipe.
Lowest level of pipe	Lowest level of the pipe (called z_d in Figure 4.31).
Angle of pipe	Horizontal angle of the lowest straight part of the configuration.
Pulling direction product pipe	The pulling force at characteristics points can be calculated for a pulling direction *From left to right* (i.e. the left point is the entry point) and *From right to left* (i.e. the right point is the entry point).
Segment length	Length of the pipeline segment, in m. If the pipeline is not installed segmentally, use a value larger than the total length of the pipeline.
Slope constant length	The length of the pipeline situated on a slope with an angle equal to the entry angle, in m. **NOTE:** To model overbending, enter a length of 0 m.

4.6.2 Product Pipe Material Data

4.6.2.1 Product Pipe Material Data for HDD

If the *Horizontal directional drilling* option in the *Model* window (section 4.1.1) is selected, click *Pipe* on the menu bar and then choose *Product Pipe Material Data* to open the *Product Pipe Material Data* window in which the characteristics of the pipe material can be entered. This data will be used for the strength calculation. Depending on the choice between steel and polyethylene, different values for the parameters need to be specified.

Steel pipe

Different types of steel pipes can be selected from the database (see Figure 4.33). User-defined values can also be defined for a steel pipeline.

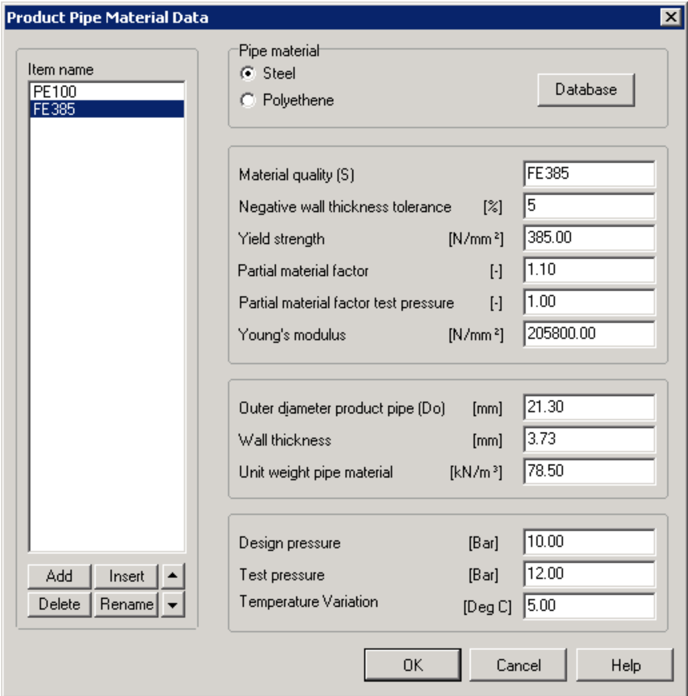
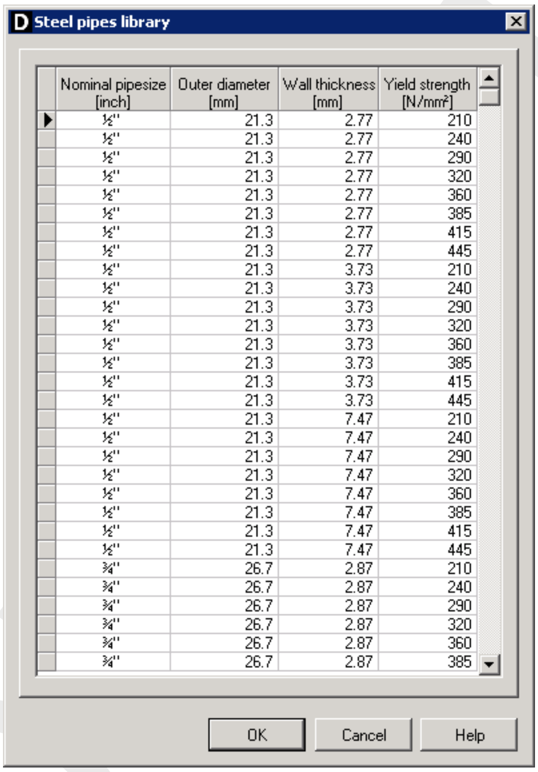


Figure 4.33: *Product Pipe Material Data window (Steel)*

Pipe material	Choice between steel or polyethylene.
	Click this button to import the name, the outer diameter, the wall thickness and the yield strength of a pipe material from the D-GEO PIPELINE library (see Figure 4.33).
Material quality	Description of the steel quality. The data in this field is used in the report.
Negative wall thickness tolerance	Tolerance on the wall thickness of the pipe ($\delta_{\rm t}$) in %. This value is used to determine the minimum wall thickness in the strength calculation.
Yield strength	Yield strength of the pipe ($R_{\rm eb}$) in N/mm^2.
Partial material factor	Partial material factor of the pipe ($\gamma_{\rm m}$). The default value is 1.1.
Partial material factor test pressure	Partial material factor of the pipe used for the calculation of the stresses caused by test pressure ($\gamma_{\rm m;test}$). The default value is 1.
Young's modulus	Modulus of elasticity of the pipe ($E_{\rm b}$) in N/mm^2. For steel, the default value is 205800 N/mm^2. It is used to determine the stresses in the pipeline in a strength calculation.
Outer diameter product pipe (Do)	Outer diameter of the product pipe ($D_{\rm o}$) in mm.
Wall thickness	Wall thickness of the pipe ($d_{\rm n}$) in mm.
Unit weight pipe material	Unit weight of the pipe material ($\gamma_{\rm b}$), used to determine the pulling force in the pipeline. For steel, the default value is 78.5 kN/m^3.
Design pressure	Design pressure ($p_{\rm d}$) in Bar, used to determine the stresses caused by internal pressure in LC 2 (section 25.5.3) and in LC 4 (section 25.5.5).

Test pressure	Test pressure (p_t) in Bar, used to determine the stresses caused by test pressure in LC 2 (section 25.5.3) and in LC 4 (section 25.5.5).
Temperature variation	Temperature variation (Δt) in °C, used to determine the stresses caused by temperature variation in LC 4 (section 25.5.5).

When clicking the *Database* button Database, the *Steel pipes library* window appears (Figure 4.34) in which the material quality (i.e. nominal pipe size), the outer diameter, the wall thickness and the yield strength of different steel pipes can be imported.



Nominal pipesize [inch]	Outer diameter [mm]	Wall thickness [mm]	Yield strength [N/mm²]
½"	21.3	2.77	210
½"	21.3	2.77	240
½"	21.3	2.77	290
½"	21.3	2.77	320
½"	21.3	2.77	360
½"	21.3	2.77	385
½"	21.3	2.77	415
½"	21.3	2.77	445
½"	21.3	3.73	210
½"	21.3	3.73	240
½"	21.3	3.73	290
½"	21.3	3.73	320
½"	21.3	3.73	360
½"	21.3	3.73	385
½"	21.3	3.73	415
½"	21.3	3.73	445
½"	21.3	7.47	210
½"	21.3	7.47	240
½"	21.3	7.47	290
½"	21.3	7.47	320
½"	21.3	7.47	360
½"	21.3	7.47	385
½"	21.3	7.47	415
½"	21.3	7.47	445
¾"	26.7	2.87	210
¾"	26.7	2.87	240
¾"	26.7	2.87	290
¾"	26.7	2.87	320
¾"	26.7	2.87	360
¾"	26.7	2.87	385

Figure 4.34: *Steel pipes library window*

Polyethylene pipe

Different types of polyethylene pipes can be selected from the database (see Figure 4.36). User-defined values can also be defined for a PE pipeline.

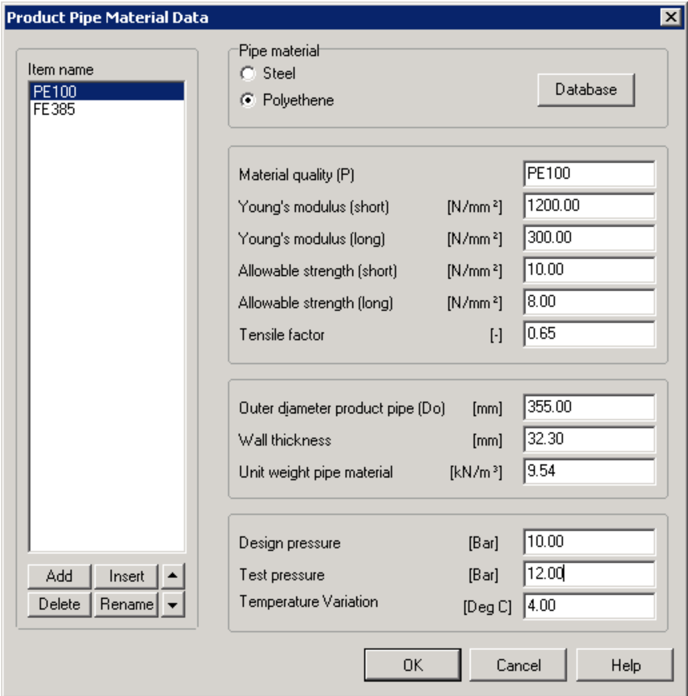
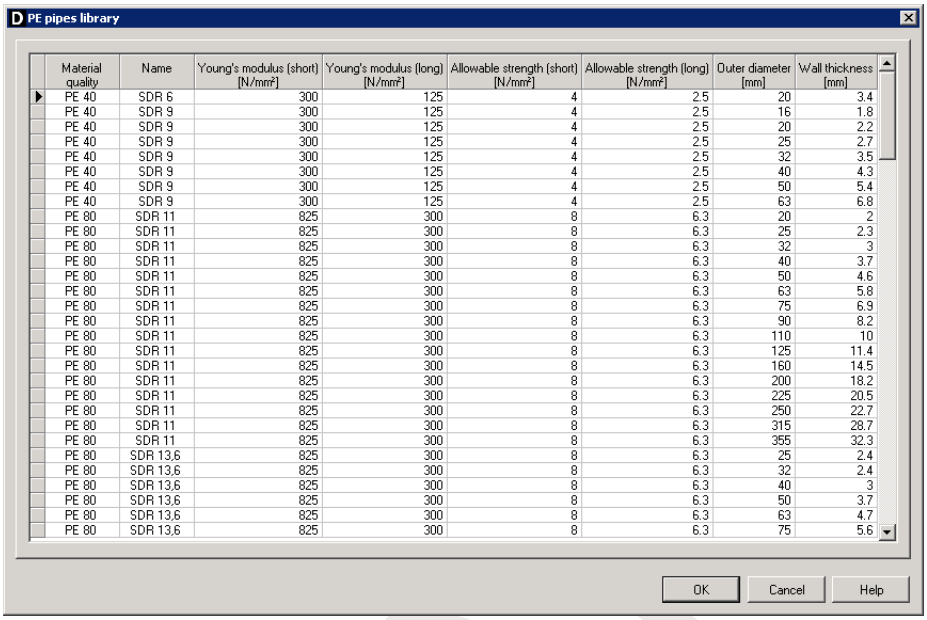


Figure 4.35: *Product Pipe Material Data window (Polyethylene)*

Pipe material	Choice between steel or polyethylene.
Database	Click this button to import the name, the outer diameter, the wall thickness and the yield strength of a pipe material from the D-GEO PIPELINE library (see Figure 4.36).
Material quality	Description of the polyethylene quality. The data in this field is used in the report.
Young's modulus (short)	Modulus of elasticity of the pipe (E_b) at short term in N/mm^2.
Young's modulus (long)	Modulus of elasticity of the pipe (E_b) at long term in N/mm^2.
Allowable strength (short)	Yield strength of the pipe at sort term ($R_{\text{eb;short}}$) in N/mm^2.
Allowable strength (long)	Yield strength of the pipe at long term ($R_{\text{eb;long}}$) N/mm^2.
Tensile factor	The tensile factor a (also called alpha pipe material) is the relation between the allowable tensile strength and the allowable bending strength. The default value is 0.65.
Outer diameter product pipe (Do)	Outer diameter of the product pipe (D_o) in mm.
Wall thickness	Wall thickness of the pipe (d_n) in mm, used to determine the stresses in a strength calculation.
Unit weight pipe material	Unit weight of the pipe material (γ_b), used to determine the pulling force in the pipeline. For PE, the default value is 9.54 kN/m^3.
Design pressure	Design pressure (p_d) in Bar, used to determine the stresses caused by internal pressure in LC 2 (section 25.5.3) and in LC 4 (section 25.5.5).
Test pressure	Test pressure (p_t) in Bar, used to determine the stresses caused by test pressure in LC 2 (section 25.5.3) and in LC 4 (section 25.5.5).
Temperature variation	Temperature variation (Δt) in °C, used to determine the stresses caused by temperature variation in LC 4 (section 25.5.5).

When clicking the *Database* button, the *PE pipes library* window appears (Figure 4.36) in which the material quality, the Young's modules (short and long), the allowable strengths (short and long), the outer diameter and the wall thickness of different PE pipes can be imported.



PE pipes library

Material quality	Name	Young's modulus (short) [N/mm²]	Young's modulus (long) [N/mm²]	Allowable strength (short) [N/mm²]	Allowable strength (long) [N/mm²]	Outer diameter [mm]	Wall thickness [mm]
PE 40	SDR 6	300	125	4	2.5	20	3.4
PE 40	SDR 9	300	125	4	2.5	16	1.8
PE 40	SDR 9	300	125	4	2.5	20	2.2
PE 40	SDR 9	300	125	4	2.5	25	2.7
PE 40	SDR 9	300	125	4	2.5	32	3.5
PE 40	SDR 9	300	125	4	2.5	40	4.3
PE 40	SDR 9	300	125	4	2.5	50	5.4
PE 40	SDR 9	300	125	4	2.5	63	6.8
PE 80	SDR 11	825	300	8	6.3	20	2
PE 80	SDR 11	825	300	8	6.3	25	2.3
PE 80	SDR 11	825	300	8	6.3	32	3
PE 80	SDR 11	825	300	8	6.3	40	3.7
PE 80	SDR 11	825	300	8	6.3	50	4.6
PE 80	SDR 11	825	300	8	6.3	63	5.8
PE 80	SDR 11	825	300	8	6.3	75	6.9
PE 80	SDR 11	825	300	8	6.3	90	8.2
PE 80	SDR 11	825	300	8	6.3	110	10
PE 80	SDR 11	825	300	8	6.3	125	11.4
PE 80	SDR 11	825	300	8	6.3	160	14.5
PE 80	SDR 11	825	300	8	6.3	200	18.2
PE 80	SDR 11	825	300	8	6.3	225	20.5
PE 80	SDR 11	825	300	8	6.3	250	22.7
PE 80	SDR 11	825	300	8	6.3	315	28.7
PE 80	SDR 11	825	300	8	6.3	355	32.3
PE 80	SDR 13,6	825	300	8	6.3	25	2.4
PE 80	SDR 13,6	825	300	8	6.3	32	2.4
PE 80	SDR 13,6	825	300	8	6.3	40	3
PE 80	SDR 13,6	825	300	8	6.3	50	3.7
PE 80	SDR 13,6	825	300	8	6.3	63	4.7
PE 80	SDR 13,6	825	300	8	6.3	75	5.6

OK Cancel Help

Figure 4.36: *PE pipes library window*

4.6.2.2 Product Pipe Material Data for Micro tunneling

If the *Micro tunneling* option in the *Model* window (section 4.1.1) is selected, click *Pipe* on the menu bar and then choose *Product Pipe Material Data* to open the *Product Pipe Material Data* window in which the characteristics of the pipe material can be entered. Depending on the choice between steel, synthetic and concrete (Figure 4.37), different parameters need to be specified.

Figure 4.37: *Product Pipe Material Data window, Pipe material sub-window*

Steel or Concrete pipe

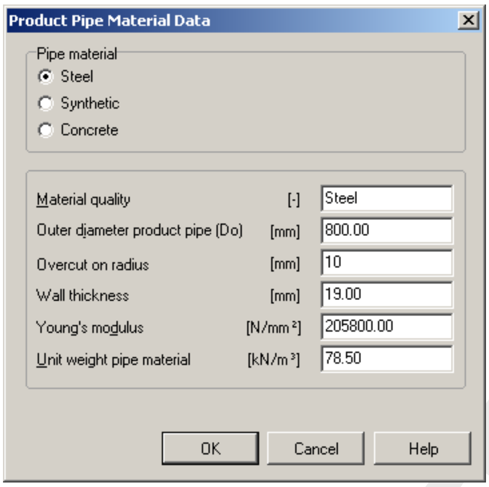


Figure 4.38: *Product Pipe Material Data window (Steel or Concrete pipe, Micro Tunneling model)*

Material quality	Description of the material quality. The data in this field is used in the report.
Outer diameter product pipe (Do)	Outer diameter of the product pipe (D_{o}) in mm.
Overcut on radius	Difference between the hole radius and the outer radius of the product pipe (l_{overcut}) in mm.
Wall thickness	Wall thickness of the pipe (d_{n}) in mm.
Young's modulus	Modulus of elasticity of the pipe (E_{b}) in N/mm^2.
Unit weight pipe material	Unit weight of the pipe material (γ_{b}) in kN/m^3. Default values are 78.5 and 26 kN/m^3 respectively for *Steel* and *Concrete* pipe.

Synthetic pipe

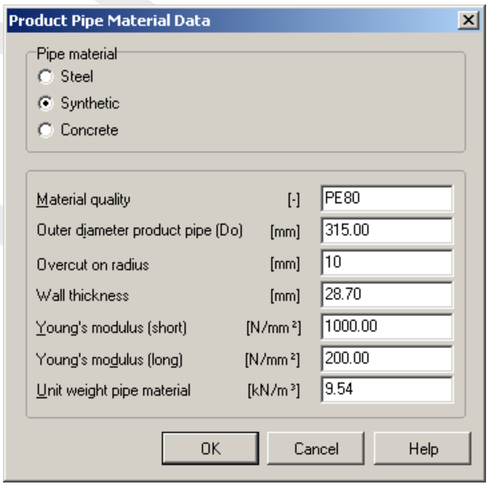


Figure 4.39: *Product Pipe Material Data window (Synthetic pipe, Micro tunneling model)*

Material quality	Description of the material quality. The data in this field is used in the report.
Outer diameter product pipe (Do)	Outer diameter of the product pipe (D_{o}) in mm.

Overcut on radius	Difference between the hole radius and the outer radius of the product pipe (l_{overcut})in mm.
Wall thickness	Wall thickness of the pipe (d_{n}) in mm.
Young's modulus (short)	Modulus of elasticity of the pipe (E_{b}) at short term in N/mm^2.
Young's modulus (long)	Modulus of elasticity of the pipe (E_{b}) at long term in N/mm^2.
Unit weight pipe material	Unit weight of the synthetic material (γ_{b}) in kN/m^3. The default value is 9.54 kN/m^3.

4.6.2.3 Product Pipe Material Data for Direct Pipe

If the *Direct Pipe* option in the *Model* window (section 4.1.1) is selected, click *Pipe* on the menu bar and then choose *Product Pipe Material Data* to open the *Product Pipe Material Data* window in which the characteristics of the pipe material can be entered. For both the pipe as well as the machine different parameters need to be specified (Figure 4.40).

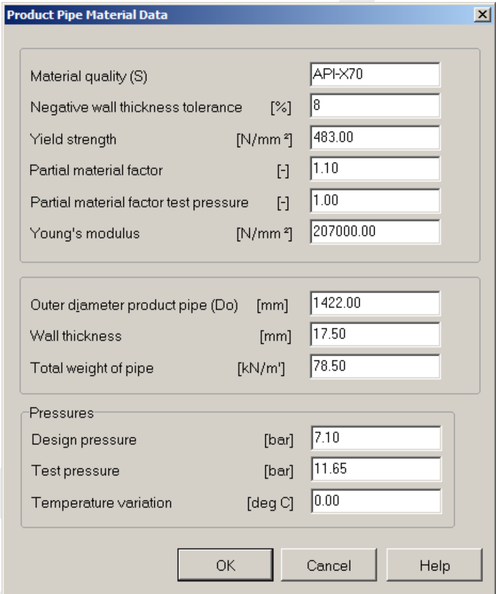


Figure 4.40: *Product Pipe Material Data window (Direct Pipe model)*

Refer to the table in section 4.6.2.1 (below Figure 4.33) for the definition of the parameters.

4.6.3 Engineering Data

In the *Pipe* menu, choose the *Engineering Data* option to open the *Engineering Data* window. The window displayed depends on the selected model.

4.6.3.1 Engineering Data for HDD

If the *Horizontal directional drilling* option in the *Model* window (section 4.1.1) is selected, the *Engineering Data* window shown in Figure 4.41 is displayed in which data on the strength calculation of the pipe can be defined (see chapter 25 for background information).

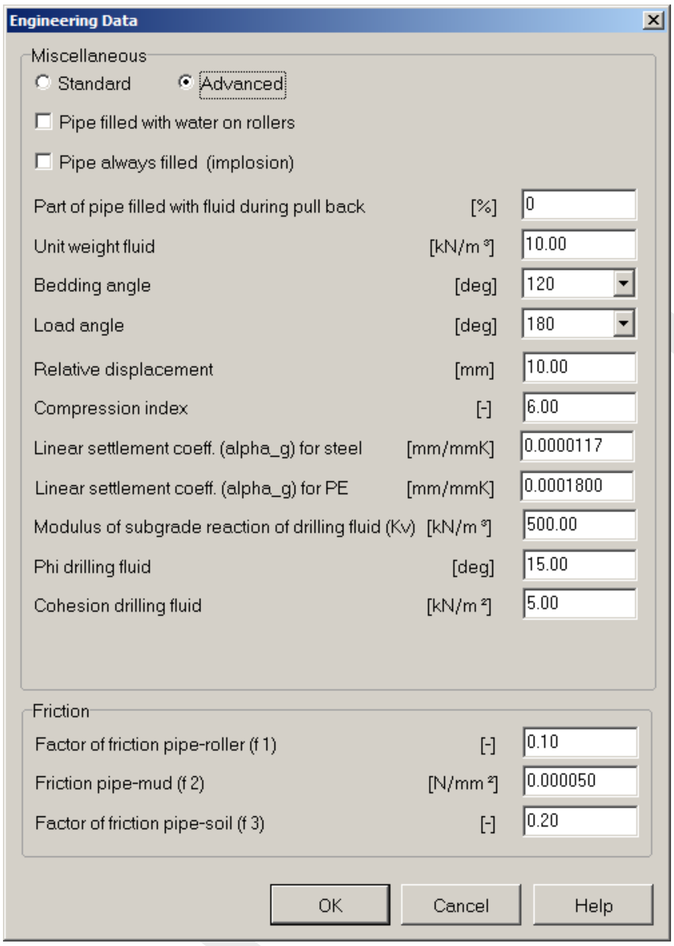


Figure 4.41: *Engineering Data window (HDD)*

Standard/Advanced	Select *Advanced* to display and modify some of the Miscellaneous parameters (*Relative displacement*, *Compression index*, *Modulus of subgrade reaction of drilling fluid*, *Phi drilling fluid*, *Cohesion drilling fluid*). If *Standard* is selected, then D-GEO PIPELINE will use the default values for the five mentioned parameters).
Pipe filled with water on rollers	Mark this check-box if the pipe is filled with water on rollers.
Pipe always filled (implosion)	Mark this check-box if the pipe is filled with water in all stages. If the pipe is completely filled, the filling fluid gives an internal fluid pressure called filling resistance p_{fill}, see Equation 25.68 in section 25.8.1.
Part of pipe filled with fluid during pull back	Part of the cross-section of the pipe filled with fluid (P_{w}) in %. Uplift forces resulting from buoyancy of the product pipe can be reduced by filling a part of the cross-section with water. This will reduce the pulling force.
Unit weight fluid	Unit weight of the fluid filling (γ_{fill}).

Bedding angle	The bedding angle β (see Figure 4.42). The default value is 120°.
Load angle	The load angle α (see Figure 4.42). The default value is 180°.
Relative displacement	Relative displacement between soil columns, necessary for full development of friction (δ_{d}). The default value is 10 mm.
Compression index	Average compression index of the layers in which the pipe is installed (C). The default value for a very compressible soil sequence is 6.
Linear settlement coeff. (alpha_g) for steel	Linear settlement coefficient α_g for steel (average over the temperature variation Δt). The default value for steel is 0.0000117 (mm/mm)K^{-1}.
Linear settlement coeff. (alpha_g) for PE	Linear settlement coefficient α_g for PE (average over the temperature variation Δt). The default value for PE is 0.00018 (mm/mm)K^{-1}.
Modulus of subgrade reaction of drilling fluid (Kv)	The modulus of subgrade reaction (also called bedding constant) of the drilling fluid after stiffening ($k_{\text{v;df}}$). The default value is 500 kN/m^3.
Phi drilling fluid	Angle of internal friction of the stiffened drilling fluid (φ_{df}). The default value is 15°.
Cohesion drilling fluid	Cohesion of the stiffened drilling fluid (c_{df}). The default value is 5 kN/m^2.
Factor of friction pipe-roller (f1)	Factor of friction between the product pipe and the rollers on the pipe-roller (f_1). During the pullback operation this part of the pulling force will decrease. The default value is 0.1.
Friction pipe-drilling fluid (f2)	Friction between the drilling fluid and the pipeline (f_2). The default value is 0.00005 N/mm^2.
Factor of friction pipe-soil (f3)	Factor of friction between the product pipe and the soil (f_3). The friction between pipe and soil is influenced by buoyancy of the pipeline in the drilling fluid. The default value is 0.2.

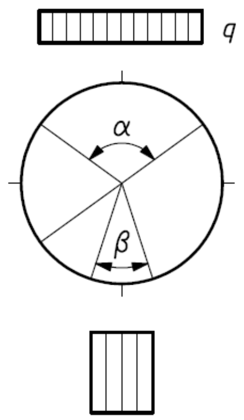


Figure 4.42: *Definition of the bedding angle β and the load angle α*

4.6.3.2 Engineering Data for Micro tunneling

If the *Micro tunneling* option in the *Model* window (section 4.1.1) is selected, the *Engineering Data* window shown in Figure 4.43 is displayed. See chapter 26 for background information.

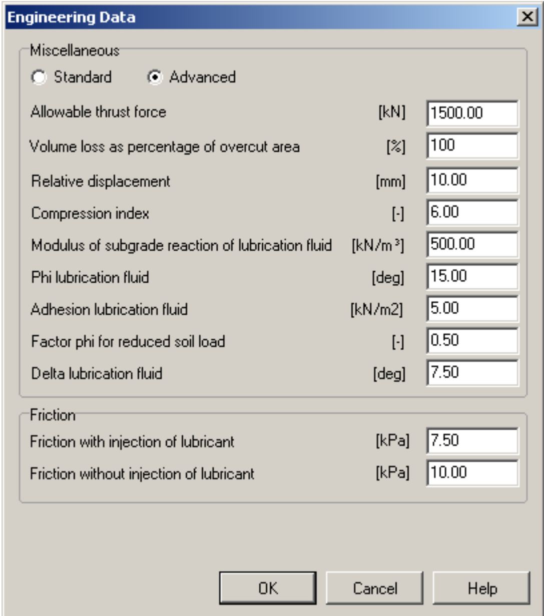


Figure 4.43: *Engineering Data window (Micro tunneling)*

Standard/Advanced	Select *Advanced* to display and modify some of the Miscellaneous parameters (Relative displacement, Compression index, Modulus of subgrade reaction of the stiffened drilling fluid, Phi drilling fluid, Cohesion drilling fluid). If *Standard* is selected, then D-GEO PIPELINE will use the default values for the five mentioned parameters).
Allowable thrust force	The maximum allowable thrust force is usually specified by the manufacturer of the pipe.
Volume loss as percentage of overcut area	The volume loss determines the subsidence at the surface (i.e. the excess soil removed by the Micro Tunneling Boring Machine).
Relative displacement	Relative displacement between soil columns, necessary for full development of friction (δ_{d}). The default value is 10 mm.
Compression index	Average compression index of the layers in which the pipe is installed (C). The default value for a very compressible soil sequence is 6.
Modulus of subgrade reaction of lubrification fluid	The modulus of subgrade reaction (also called bedding constant) of the lubrification fluid ($k_{\mathrm{v;lub\ fluid}}$). The default value is 500 kN/m^3.
Phi lubrication fluid	Angle of internal friction of the lubrification fluid ($\varphi_{\mathrm{lub\ fluid}}$). The default value is 15°.
Adhesion lubrification fluid	Adhesion of the lubrification fluid ($a_{\mathrm{lub\ fluid}}$). The default value is 5 kN/m^2.
Factor phi for reduced soil load	Safety factor applied on the reduced soil stress. The default value is 0.5.
Delta lubrification fluid	Delta angle of the lubrification fluid. The default value is 7.5°.
Friction with injection of lubricant	The friction between the soil and the pipe in case of injection of lubricant (M) used for the calculation of the thrust forces F_{m} (see Equation 26.8 in section 26.1.4).

Friction without injection of lubricant	The friction between the soil and the pipe in case of no injection of lubricant (M) used for the calculation of the thrust forces F_m (see Equation 26.8 in section 26.1.4).

4.6.3.3 Engineering Data for Construction in trench

If the *Construction in trench* option in the *Model* window (section 4.1.1) is selected, the *Engineering Data* window shown in Figure 4.44 is displayed. In this window, information about the filling can be entered and will be used to determine the value of the percentage of compaction μ used in the calculation of the initial (or actual) vertical stress, see section 23.4 for background information.

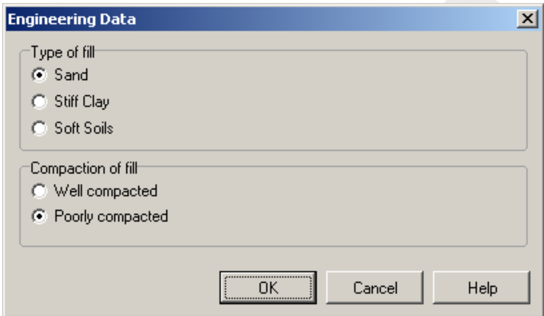


Figure 4.44: *Engineering Data window (Construction in trench)*

Type of fill	Select the type of fill used for the filling of the trench: *Sand*, *Stiff Clay* or *Soft Soils*.
Compaction of fill	Select the type of compaction of the filling soil: *Well compacted* or *Poorly compacted*.

4.6.3.4 Engineering Data for Direct Pipe

If the *Direct Pipe* option in the *Model* window (section 4.1.1) is selected, the *Engineering Data* window shown in Figure 4.45 is displayed. In this window, information about the friction coefficients can be entered and will be used to calculate the thrust force.

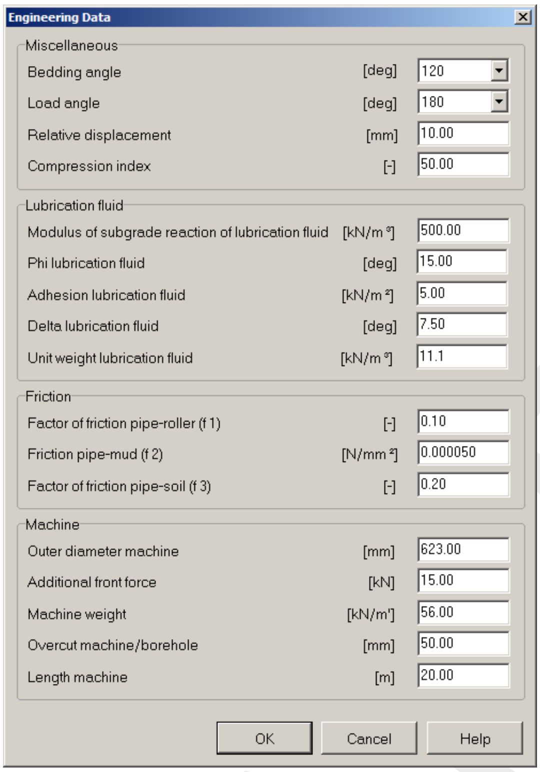


Figure 4.45: *Engineering Data window (Direct Pipe)*

Bedding angle	The bedding angle β (see Figure 4.42). The default value is 120°.
Load angle	The load angle α (see Figure 4.42). The default value is 180°.
Relative displacement	Relative displacement between soil columns, necessary for full development of friction (δ_{d}). The default value is 10 mm.
Compression index	Average compression index of the layers in which the pipe is installed (C). The default value for a very compressible soil sequence is 6.
Linear settlement coeff. (alpha_g) for steel	Linear settlement coefficient α_g for steel (average over the temperature variation Δt). The default value for steel is 0.0000117 (mm/mm)K^{-1}.
Modulus of subgrade reaction of lubrication fluid	The modulus of subgrade reaction (also called bedding constant) of the lubrication fluid ($k_{\text{v;lub fluid}}$). The default value is 500 kN/m^3.
Phi lubrication fluid	Angle of internal friction of the lubrification fluid ($\varphi_{\text{lub fluid}}$). The default value is 15°.
Adhesion lubrification fluid	Adhesion of the lubrification fluid ($a_{\text{lub fluid}}$). The default value is 5 kN/m^2.
Delta lubrification fluid	Delta angle of the lubrification fluid. The default value is 7.5°.
Unit weight lubrification fluid	Unit weight of the lubrification fluid ($\gamma_{\text{lub fluid}}$). The default value is 11.1 kN/m^3.
Factor of friction pipe-roller (f1)	Factor of friction between the product pipe and the rollers on the pipe-roller (f_1). The default value is 0.1.
Friction pipe-drilling fluid (f2)	Friction between the drilling fluid and the pipeline (f_2). The default value is 0.0001 N/mm^2.
Factor of friction pipe-soil (f3)	Factor of friction between the product pipe and the soil (f_3). The default value is 0.3. In case of collapse of the borehole 0.6 is recommended.

Outer diameter machine	Outer diameter of the pipe thruster ($D_{\text{o,m}}$) in mm.
Additional front force	The mechanical force in addition to the slurry support pressure at the cutting wheel (force used to cut the soil) (F_{add}) in kN. The default value is 10 kN.
Machine weight	Effective weight of the pipe thruster in bentonite ($g_{\text{eff,m}}$) in kN/m.
Overcut machine/ borehole	The difference in diameter of the borehole and the outer diameter of the pipe thruster in mm.
Length machine	Length of the pipe thruster (L_{m}) in m.

4.6.4 Drilling Fluid Data

In the *Pipe* menu, choose the *Drilling Fluid Data* option to open the *Drilling Fluid Data* window in which the drill pipe and borehole dimensions, the characteristics of drilling fluid flow, and the properties of the drilling fluid can be defined. For the *Direct Pipe* module, only the properties of the drilling fluid can be defined. For background information, see chapter 24.

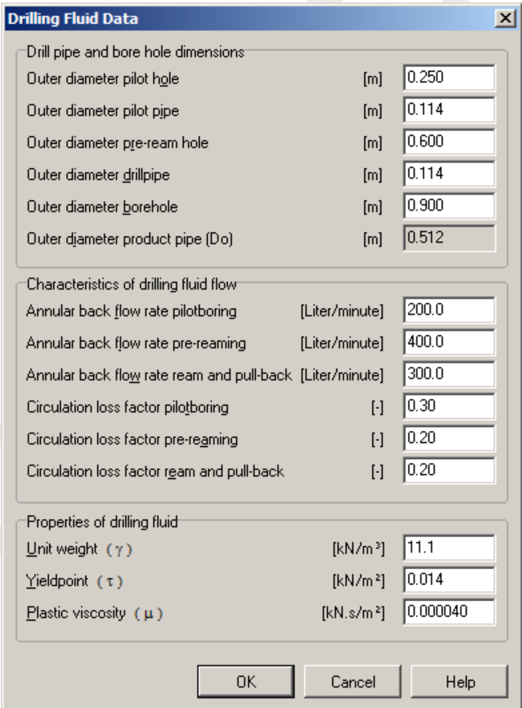


Figure 4.46: *Drilling Fluid Data window*

Outer diameter pilot hole	Outer diameter of the hole during the pilot hole drilling [m].
Outer diameter pilot pipe	Outer diameter of the pipe during the pilot hole drilling [m].
Outer diameter pre-ream hole	Outer diameter of the hole during the pre-reaming of the product pipeline [m].
Outer diameter drill pipe	Outer diameter of the pipe during the pre-reaming of the product pipeline [m].
Outer diameter borehole	Outer diameter of the hole during the pullback of the product pipeline [m].

Outer diameter product pipe (Do)	Outer diameter of the (bundled) pipe during the pullback of the product pipeline. This value is automatically calculated by the program using the pipe diameters of the different pipes as inputted in the *Product Pipe Material Data* window (see section 4.6.2.1). The following formula is used: $D_{\text{eq}} = \sqrt{\sum_{i=1}^{n} D_{o;i}^2}$
Annular back flow rate pilot boring	Annular back flow rate (Q_{ann}) during the pilot hole drilling, in liter/minute.
Annular back flow rate pre-reaming	Annular back flow rate (Q_{ann}) during the pre-reaming stage, in liter/minute.
Annular back flow rate ream and pullback	Annular back flow rate (Q_{ann}) during the pullback stage, in liter/minute.
Circulation loss factor pilot boring	Circulation loss factor (f_{loss}) during the pilot-hole drilling. The default value is 0.3.
Circulation loss factor pre-reaming	Circulation loss factor (f_{loss}) during the pre-reaming stage. The default value is 0.2.
Circulation loss factor ream and pull-back	Circulation loss factor (f_{loss}) during the pullback stage . The default value is 0.2.
Unit weight (γ)	Unit weight of the drilling fluid (γ_{df}). The default value is 11.1 kN/m^3.
Yield point (τ)	Yield point of the drilling fluid (τ_{df}). The default value is 0.014 kN/m^2.
Plastic viscosity (μ)	Plastic viscosity of the drilling fluid (μ_{df}). The default value is 0.00004 kN.s/m^2.

The annular back-flow depends mainly on the size of the borehole and the pump system on the type of drilling rig used. The circulation loss factor depends on the soil layers through which the drilling is performed. The circulation loss factor indicates the loss of the drilling fluid in the soil surrounding the borehole.

The properties of the drilling fluid (γ_{df}, τ_{df} and μ_{df}) can be obtained from the drilling fluid manufacturer.

4.7 Defaults menu

4.7.1 Factors

In the *Defaults* menu, choose the *Factor* option to open the *Factor* input window. The content of the window depends on the model:

- ◇ Refer to section 4.7.1.1 for HDD
- ◇ Refer to section 4.7.1.2 for Micro tunneling
- ◇ Refer to section 4.7.1.3 for Construction in trench
- ◇ Refer to section 4.7.1.4 for Direct Pipe

4.7.1.1 Factors for HDD

If the *Horizontal directional drilling* option in the *Model* window (section 4.1.1) is selected, the factors for loads and strength parameters according to either the Dutch standard NEN 3650 or the European standard CEN can be specified in the *Factors* window. Depending on the choice of the type of material (steel or polyethylene), different factors need to be specified.

Factors for HDD – Dutch standard NEN – Polyethylene pipe

If the Dutch standard NEN was selected in the the *Model* window (section 4.1.1) and if a polyethylene material was selected in the *Product Pipe Material Data* window (section 4.6.2.1), the window in Figure 4.47 is displayed.

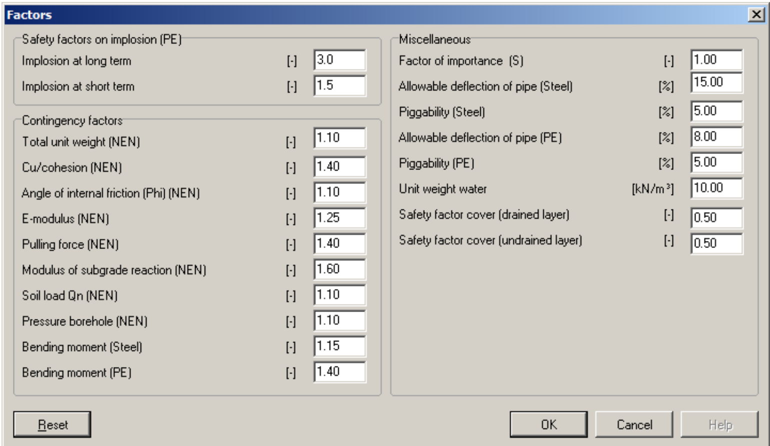


Figure 4.47: *Factors window (HDD) for polyethylene pipe, acc. to the Dutch standard NEN*

Implosion at long term	Safety factor on implosion at long term ($\gamma_{\text{imp;long}}$). The default value is 3, as prescribed in paragraph 8.5.5.1 of NEN 3650-3 (NEN, 2012c).
Implosion at short term	Safety factor on implosion at short term ($\gamma_{\text{imp;short}}$). The default value is 1.5, as prescribed in paragraph 8.5.5.1 of NEN 3650-3 (NEN, 2012c).
Total unit weight	Contingency factor on the total unit weight above and below the phreatic level (f_γ). The default value is 1.1, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Cu/cohesion	Contingency factor on the cohesion for drained and undrained conditions (f_{c}). The default value is 1.4, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Angle of internal friction (Phi)	Contingency factor on the angle of internal friction (f_φ). The default value is 1.1, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
E-modulus	Contingency factor on the Young's modulus (f_{E}). The default value is 1.25, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Pulling force	Contingency factor on pulling forces (f), to take into account the stochastic distribution in the value of the different friction components and the uncertainty on the model. The default value is 1.4, as prescribed in paragraph E.1.2.1 of NEN 3650-1 (NEN, 2012a). **NOTE**: According to the NEN 3650-1 (article E.1.2.3), the contingency factor on the pulling force for bundled pipelines should be increased to 1.8 because due to the pull back of the bundled pipelines the risk on higher pulling forces than calculated is present.
Modulus of subgrade reaction	Contingency factor on the modulus of subgrade reaction (f_{kv}). The default value is 1.6.
Soil load Qn	Contingency factor on the reduced neutral soil stress $Q_{\text{n,r}}$ (f_{Qn1}), used for the strength calculation of the pipeline (see section 25.5). The default value is 1.1, as prescribed in Table B.3 of NEN 3650-1 (NEN, 2012a).

Pressure borehole	Contingency factor on the pressure borehole ($f_{\text{press;bore}}$), used to check the equilibrium between drilling fluid pressure and pore pressure, see section 24.4. The default value is 1.1.
Bending moment (Steel)	Contingency factor on the bending moment (f_{M}) for steel. In paragraph E.1.3 of NEN 3650-1 (NEN, 2012a), an overall factor on bending moment (f_{k}) of 1.4 is prescribed. As this overall factor includes different contingency factors (i.e. $f_{\text{k}} = f_{\text{M}} \times f_{\text{install}} \times f_{\text{R}}$) and as f_{install} = 1.1 and f_{R} = 1.1, a default factor of 1.15 should be inputted for f_{M} to get f_{k} = 1.4 as prescribed by NEN.
Bending moment (PE)	Contingency factor on the bending moment (f_{M}) for PE. In paragraph E.1.3 of NEN 3650-1 (NEN, 2012a), an overall factor on bending moment (f_{k}) of 1.4 is prescribed. As this overall factor includes different contingency factors (i.e. $f_{\text{k}} = f_{\text{M}} \times f_{\text{install}} \times f_{\text{R}}$) and as f_{install} = 1 and f_{R} = 1, a default factor of 1.4 should be inputted for f_{M} to get f_{k} = 1.4 as prescribed by NEN.
Factor of importance (S)	Factor of importance (S). The default value is 1 (for HDD), as prescribed in paragraph 6.5 of NEN 3651 (NEN, 2012d).
Allowable deflection of pipe (Steel)	Maximum allowable deflection of the pipe (δ_0). The default value is 15% of the pipe diameter for steel, as prescribed in paragraph 11.1.5 of NEN 3651 (NEN, 2012d).
Piggability (Steel)	Maximum allowable deflection of the pipe for piggability (δ_1). If this value is exceeded, the pig (i.e. tool or vehicle that moves through the interior of the pipeline for purposes of inspecting, dimensioning, or cleaning) can be damaged or stuck. The default value is 5% of the pipe diameter.
Allowable deflection of pipe (PE)	Maximum allowable deflection of the pipe (δ_0). The default value is 8% of the pipe diameter for PE, as prescribed in paragraph 11.4.1.1 of NEN 3651 (NEN, 2012d).
Piggability (PE)	Maximum allowable deflection of the pipe for piggability (δ_1). If this value is exceeded, the pig (i.e. tool or vehicle that moves through the interior of the pipeline for purposes of inspecting, dimensioning, or cleaning) can be damaged or stuck. The default value is 5% of the pipe diameter.
Unit weight water	Unit weight of water (γ_{w}). The default value is 10 kN/m^3.
Safety factor cover (drained layer)	The ratio between the maximum allowable radius of the plastic zone $R_{\text{p;max}}$ and the soil cover H (vertical distance between the ground level and the pipe center) for the calculation of the maximum allowable drilling fluid pressure in drained layer (i.e. sand), see Equation 24.28 in section 24.2.2. The default value is 0.5, as prescribed in paragraph E.2.2.2 of NEN 3650-1 (NEN, 2012a): $R_{\text{p,max}}$ = 0.5 H.
Safety factor cover (undrained layer)	The ratio between the maximum allowable radius of the plastic zone $R_{\text{p;max}}$ and the soil cover H (vertical distance between the ground level and the pipe center) for the calculation of the maximum allowable drilling fluid pressure in undrained layer (i.e. clay and peat), see Equation 24.22 in section 24.2.1. The default value is 0.5, as prescribed in paragraph E.2.2.2 of NEN 3650-1 (NEN, 2012a): $R_{\text{p,max}}$ = 0.5 H.
	Click this button to reset all values to the default values prescribed in the Dutch Standard NEN. **NOTE:** If the input values in the *Factors* window differ from the default values prescribed by NEN, the value appears in red color.

Factors for HDD – Dutch standard NEN – Steel pipe

If the Dutch standard NEN was selected in the the *Model* window (section 4.1.1) and if a steel material was selected in the *Product Pipe Material Data* window (section 4.6.2.1), the window in Figure 4.48 is displayed. Load factors are used for the strength calculation of the pipeline (see section 25.5).

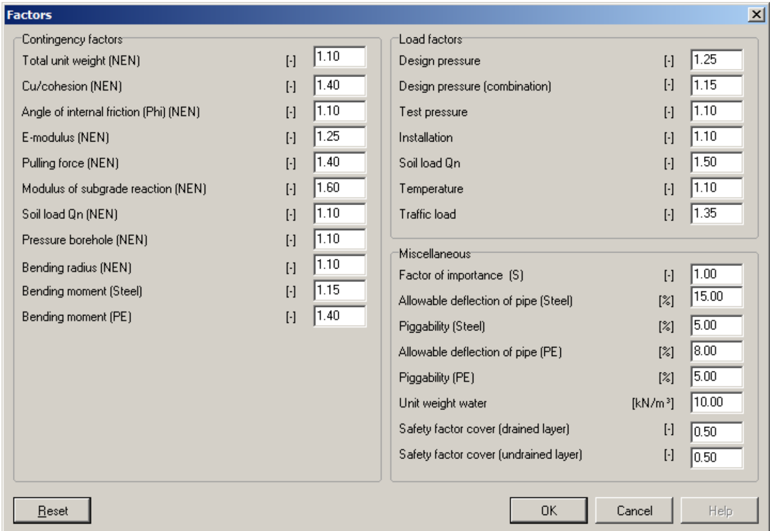


Figure 4.48: *Factors window (HDD) for steel pipe, acc. to the Dutch standard NEN*

Total unit weight	Contingency factor on the total unit weight above and below the phreatic level (f_γ). The default value is 1.1, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Cu/cohesion	Contingency factor on the cohesion for drained and undrained conditions (f_c). The default value is 1.4, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Angle of internal friction (Phi)	Contingency factor on the angle of internal friction (f_φ). The default value is 1.1, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
E-modulus	Contingency factor on the Young's modulus (f_E). The default value is 1.25, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Pulling force	Contingency factor on pulling forces (f), to take into account the stochastic distribution in the value of the different friction components and the uncertainty on the model. The default value is 1.4, as prescribed in paragraph E.1.2.1 of NEN 3650-1 (NEN, 2012a). **NOTE**: According to the NEN 3650-1 (article E.1.2.3), the contingency factor on the pulling force for bundled pipelines should be increased to 1.8 because due to the pull back of the bundled pipelines the risk on higher pulling forces than calculated is present.
Modulus of subgrade reaction	Contingency factor on the modulus of subgrade reaction (f_{kv}). The default value is 1.6.
Soil load Qn	Contingency factor on the reduced neutral soil stress $Q_{n,r}$ (f_{Qn1}), used for the strength calculation of the pipeline (see section 25.5). The default value is 1.1, as prescribed in Table B.3 of NEN 3650-1 (NEN, 2012a).
Pressure borehole	Contingency factor on the pressure borehole ($f_{press;bore}$), used to check the equilibrium between drilling fluid pressure and pore pressure, see section 24.4. The default value is 1.1.

Bending radius	Contingency factor on the bending radius (f_R) used for the determination of the axial stress in the strength calculation, see section 25.5. The default value is 1.1.
Bending moment (Steel)	Contingency factor on the bending moment (f_M) for steel. In paragraph E.1.3 of NEN 3650-1 (NEN, 2012a), an overall factor on bending moment (f_k) of 1.4 is prescribed. As this overall factor includes different contingency factors (i.e. $f_k = f_M \times f_{install} \times f_R$) and as $f_{install}$ = 1.1 and f_R = 1.1, a default factor of 1.15 should be inputted for f_M to get f_k = 1.4 as prescribed by NEN.
Bending moment (PE)	Contingency factor on the bending moment (f_M) for PE. In paragraph E.1.3 of NEN 3650-1 (NEN, 2012a), an overall factor on bending moment (f_k) of 1.4 is prescribed. As this overall factor includes different contingency factors (i.e. $f_k = f_M \times f_{install} \times f_R$) and as $f_{install}$ = 1 and f_R = 1, a default factor of 1.4 should be inputted for f_M to get f_k = 1.4 as prescribed by NEN.
Design pressure	Load factor on the design pressure (f_{pd}). The default value is 1.25 as prescribed in Table 2 of NEN 3650-2 (NEN, 2012b).
Design pressure (combination)	Load factor on the design pressure when used in combination ($f_{pd;comb}$). The default value is 1.15 as prescribed in Table 2 of NEN 3650-2 (NEN, 2012b).
Test pressure	Load factor on the test pressure (f_{pt}). The default value is 1.1 as prescribed in Table 2 of NEN 3650-2 (NEN, 2012b).
Installation	Load factor on the installation ($f_{install}$). The default value is 1.1 as prescribed in Table 2 of NEN 3650-2 (NEN, 2012b).
Soil load Qn	Load factor on the reduced neutral soil stress $Q_{n,r}$ (f_{Qn2}). The default value is 1.5.
Temperature	Load factor on the stress due to temperature variation (f_{temp}). The default value is 1.1 as prescribed in Table 2 of NEN 3650-2 (NEN, 2012b).
Traffic load factor	The load factor on the traffic load f_{qv}, see section 23.14. The default value is 1.35, as prescribed in Table 2 of NEN 3650-2 (NEN, 2012b).
Factor of importance (S)	Factor of importance (S). The default value is 1 (for HDD), as prescribed in paragraph 6.5 of NEN 3651 (NEN, 2012d).
Allowable deflection of pipe (Steel)	Maximum allowable deflection of the pipe (δ_0). The default value is 15% of the pipe diameter for steel, as prescribed in paragraph 11.1.5 of NEN 3651 (NEN, 2012d).
Piggability (Steel)	Maximum allowable deflection of the pipe for piggability (δ_1). If this value is exceeded, the pig (i.e. tool or vehicle that moves through the interior of the pipeline for purposes of inspecting, dimensioning, or cleaning) can be damaged or stuck. The default value is 5% of the pipe diameter.
Allowable deflection of pipe (PE)	Maximum allowable deflection of the pipe (δ_0). The default value is 8% of the pipe diameter for PE, as prescribed in paragraph 11.4.1.1 of NEN 3651 (NEN, 2012d).
Piggability (PE)	Maximum allowable deflection of the pipe for piggability (δ_1). If this value is exceeded, the pig (i.e. tool or vehicle that moves through the interior of the pipeline for purposes of inspecting, dimensioning, or cleaning) can be damaged or stuck. The default value is 5% of the pipe diameter.
Unit weight water	Unit weight of water (γ_w). The default value is 10 kN/m^3.

Safety factor cover (drained layer)	The ratio between the maximum allowable radius of the plastic zone $R_{\text{p;max}}$ and the soil cover H (vertical distance between the ground level and the pipe center) for the calculation of the maximum allowable drilling fluid pressure in drained layer (i.e. sand), see Equation 24.28 in section 24.2.2. The default value is 0.5, as prescribed in paragraph E.2.2.2 of NEN 3650-1 (NEN, 2012a): $R_{\text{p,max}} = 0.5\ H$.
Safety factor cover (undrained layer)	The ratio between the maximum allowable radius of the plastic zone $R_{\text{p;max}}$ and the soil cover H (vertical distance between the ground level and the pipe center) for the calculation of the maximum allowable drilling fluid pressure in undrained layer (i.e. clay and peat), see Equation 24.22 in section 24.2.1. The default value is 0.5, as prescribed in paragraph E.2.2.2 of NEN 3650-1 (NEN, 2012a): $R_{\text{p,max}} = 0.5\ H$.
	Click this button to reset all values to the default values prescribed in the Dutch Standard NEN. **NOTE:** If the input values in the *Factors* window differ from the default values prescribed by NEN, the value appears in red color.

Factors for HDD – European standard CEN – Polyethylene pipe

If the European standard CEN was selected in the the *Model* window (section 4.1.1) and if a polyethylene material was selected in the *Product Pipe Material Data* window (section 4.6.2.1), the window in Figure 4.49 is displayed.

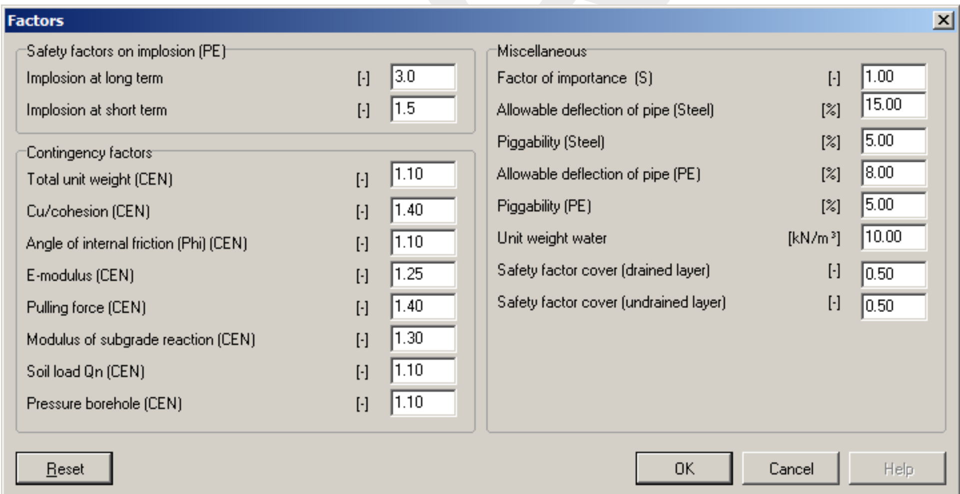


Figure 4.49: *Factors window (HDD) for polyethylene pipe, acc. to the European standard CEN*

For the definition of the parameters refer to the window for the Dutch standard NEN (see Figure 4.47), only the default values are different.

Click the  button to reset all values to the default values prescribed in the European standard CEN. If the input values in the *Factors* window differ from the default values prescribed by CEN, the value appears in red color.

Factors for HDD – European standard CEN – Steel pipe

If the European standard CEN was selected in the the *Model* window (section 4.1.1) and if a steel material was selected in the *Product Pipe Material Data* window (section 4.6.2.1), the window in Figure 4.50 is displayed.

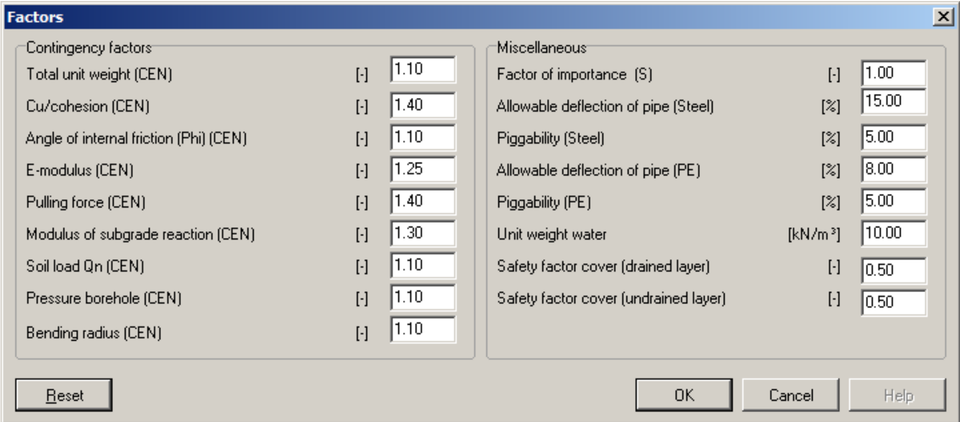


Figure 4.50: *Factors window (HDD) for steel pipe, according to the European standard CEN*

For the definition of the parameters refer to the window for the Dutch standard NEN (see Figure 4.48), only the default values are different.

Click the 

button to reset all values to the default values prescribed in the European standard CEN. If the input values in the *Factors* window differ from the default values prescribed by CEN, the value appears in red color.

4.7.1.2 Factors for Micro tunneling

If the *Micro tunneling* option in the *Model* window (section 4.1.1) is selected, the *Factors* window of Figure 4.51 is displayed in which the safety factors for soil parameters can be specified.

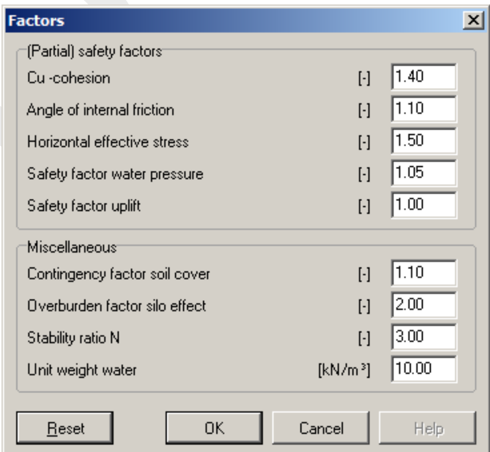


Figure 4.51: *Factors window (Micro tunneling)*

Cu/cohesion	The safety factor on the cohesion for drained and undrained conditions (f_c). The default value is 1.4, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Angle of internal friction (Phi)	The safety factor on the angle of internal friction (f_φ). The default value is 1.1, as prescribed in Table B.2 of NEN 3650-1 (NEN, 2012a).
Horizontal effective stress	The safety factor on the horizontal effective stress ($f_{\sigma \mathrm{h}}$). The default value is 1.5.
Safety factor water pressure	The safety factor on the water pressure u (f_u). The default value is 1.05.
Safety factor uplift	The safety factor on uplift (f_uplift). The default value is 1.
Contingency factor soil cover	The contingency factor on soil cover (f_cover). The default value is 1.1.
Overburden factor silo effect	The overburden factor on silo effect (f_silo). The default value is 2.
Stability ratio N	The stability ratio (N). The default value is 3. This ratio is used for the calculation of the minimal support pressure in undrained conditions, see Equation 26.2 in section 26.1.2.
Unit weight water	The unit weight of water (γ_w). The default value is 10 kN/m^3.
	Click this button to reset all values to the default values. **NOTE:** If the input values in the *Factors* window differ from the default values, the value appears in red color.

4.7.1.3 Factors for Construction in trench

If the *Construction in trench* option in the *Model* window (section 4.1.1) is selected, the *Factors* window of Figure 4.52 is displayed in which the safety factor for uplift and the unit weight of water can be specified.

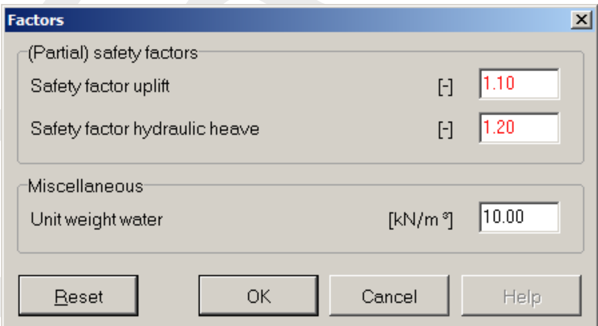


Figure 4.52: *Factors window (Construction in trench)*

Safety factor uplift	The safety factor on uplift (f_uplift). The default value is 1.
Safety factor hydraulic heave	The safety factor on hydraulic heave (f_burst). The default value is 1.
Unit weight water	Unit weight of water (γ_w). The default value is 10 kN/m^3.
	Click this button to reset all values to the default values. **NOTE:** If the input values in the *Factors* window differ from the default values, the value appears in red color.

4.7.1.4 Factors for Direct Pipe

If the *Direct Pipe* option in the *Model* window (section 4.1.1) is selected, the *Factors* window of Figure 4.53 is displayed in which the contingency factors, the load factors and the miscellaneous factors can be specified.

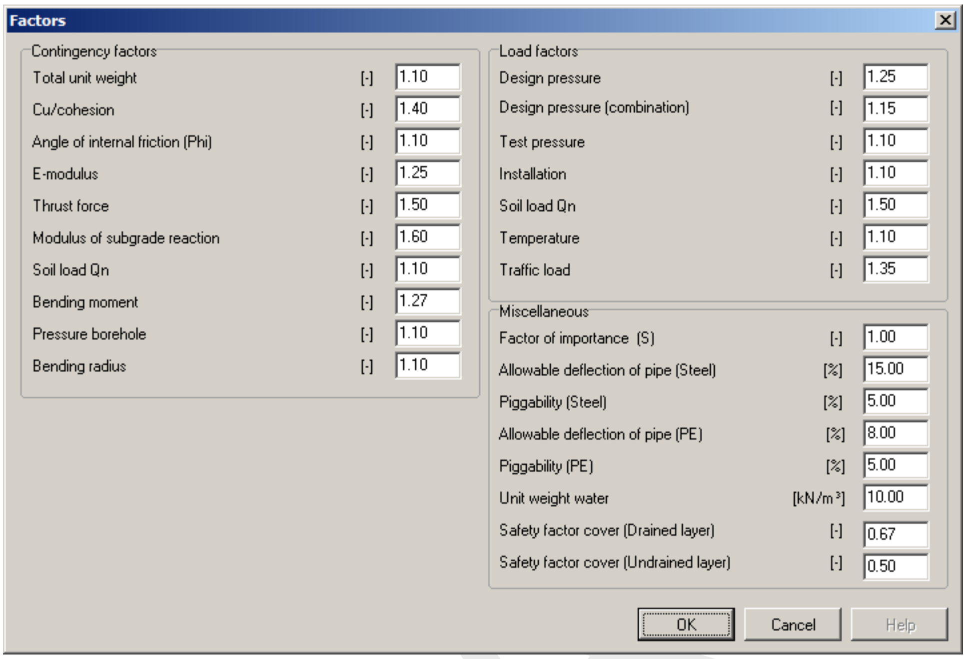


Figure 4.53: *Factors window (Direct Pipe)*

Thrust force	Contingency factor on the calculated thrust force (f_{thrust}). The default is 1.5.

Refer to the table below Figure 4.48 (HHD - Steel) for the definition of the other parameters.

4.7.2 Special Stress Analysis

If the *Horizontal directional drilling* option in the *Model* window (section 4.1.1) is selected, the *Special Stress Analysis* window of Figure 4.54 is displayed when selecting *Special Stress Analysis* from the *Defaults* menu. In this window, it is possible to choose between three types of stress analysis: a standard, a per vertical or a special analysis, as explained below.

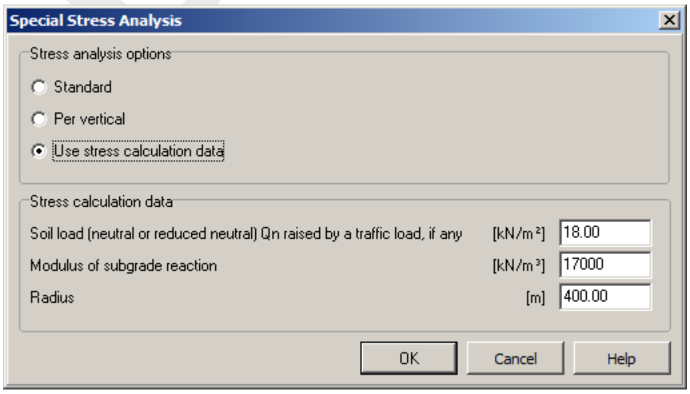


Figure 4.54: *Special Stress Analysis window (HDD)*

Stress analysis options	Three types of stress analysis are available: • A *Standard* stress analysis, performed from the *Start* option of the *Calculation* menu (see section 5.1), which uses the maximum reduced neutral soil stress and the maximum modulus of subgrade reaction of the soil calculated by D-GEO PIPELINE between all the verticals and the minimum bending radius present in the pipeline configuration. • A stress analysis *Per vertical*, performed from the *Start* option of the *Calculation* menu (see section 5.1), which uses the reduced neutral soil stress and the modulus of subgrade reaction of the soil calculated by D-GEO PIPELINE per vertical and the bending radius of the pipeline trajectory cut by the vertical. **NOTE:** If the vertical cut a straight part of the pipeline trajectory, D-GEO PIPELINE assumes a very large bending radius of 100000 m. • A “Special Stress Analysis”, performed from the *Special Stress Analysis* option of the *Calculation* menu (see section 5.2) using *Stress calculation data* (i.e user-defined values for the reduced neutral soil stress, for the modulus of subgrade reaction of the soil and for the bending radius).

If the option *Use stress calculation data* is selected, the following values must be inputted:

Soil load (neutral or reduced neutral) Qn raised by a traffic load if any	Enter the user-defined reduced neutral soil stress (in kN/m^2), used for a *Special Stress Analysis* (section 5.2).
Modulus of subgrade reaction	Enter the user-defined modulus of subgrade reaction of the soil (in kN/m^3), used for a *Special Stress Analysis* (section 5.2).
Radius	Radius of the pipeline in the ground, which is used for the calculation of the pulling force. During a standard calculation, D-GEO PIPELINE assumes the maximum present radius. With the *Special Stress Analysis* (section 5.2), an other radius can be chosen by the user.

5 Calculations

5.1 Start Calculation

On the menu bar, click *Start* in the *Calculation* menu to perform the following calculations:

◇ **Calculation of soil mechanical data**
The passive, neutral and reduced vertical stresses of the soil, the vertical coefficient of subgrade reaction, and the ultimate bearing capacity for each vertical are calculated and written to a report file (see section 6.2.4). For background information, see chapter 23].

◇ **Calculation of drilling fluid pressures (only for HDD)**
In directional drilling first a bore hole is made by a pilot drilling. This bore hole has a relatively small diameter. During the second drilling stage the initial bore hole is enlarged by pre-reaming. When the requested diameter is reached the product pipe is pulled into the bore hole. During all drilling stages a minimum required drilling fluid pressure is necessary. The bore fluid pressure induces a return flow of drilling fluid from the drilling head to the entry or exit point. The return flow transports loosened soil material. The necessary fluid pressure depends on:

- The difference in elevation between the bore hole and the exit point of the return flow;
- The minimum required pressure necessary to cause a return flow (soil material included) over a certain distance.

When the entry and exit points are not on the same level, the minimum required drilling fluid pressure depends on the direction of the drilling (from left to right or from right to left). D-GEO PIPELINE calculates the minimum required drilling fluid pressure for both cases.
The maximum allowable pressure depends on the strength of the soil around the bore-hole. When the required drilling pressure is higher than the maximum allowable pressure, there is a risk a blow out may occur. In that case, the pipeline configuration must be changed. For instance, by choosing a lower pipe level or by moving the entry or exit point.
The calculations of the minimum and maximum drilling fluid pressures for the three stages (pilot, pre-ream and pull-back) are performed in the user defined verticals. The results of the calculations are written to a report file (see section 6.2.1). For background information, see chapter 24.

◇ **Pipe stress analysis (only for HDD)**
In the pipe stress analysis, the pulling forces during the pull-back operation, the maximum acting stresses in the pipe material and the deflection of the pipeline are calculated. The calculated stresses are compared to the allowable short and long term stresses for a PE pipeline, while for a steel pipeline a total stress is calculated and compared with the allowable stress. With this option, the strength calculation is performed with the calculated reduced neutral soil load and bedding constant after the soil mechanical data has been calculated. The results of the calculations are written to a report file (see section 6.2.5 and section 6.2.6). For background information, see chapter 25.

◇ **Settlements**
The settlements of soil layers below the pipeline are calculated. For Micro Tunneling model, the subsidence are also calculated. The results of the calculations are written to a report file (see section 6.2.2 and section 6.2.3). For background information, see section 23.10 and section 26.3.

◇ **Operation parameters**

- the uplift check and the hydraulic heave check for Trenching; for background information, see chapter 27.
- the uplift check, the face support pressures and the thrust forces for Micro tunneling; for background information, see section 26.1 and section 26.2.

The results of the calculations are written to a report file (see section 6.2.7 and section 6.2.8).

5.2 Special Stress Analysis (only for HDD)

On the menu bar, click *Special Stress Analysis* in the *Calculation* menu to perform a pipe stress calculation with the user-defined values for the reduced neutral soil stress, the modulus of subgrade reaction and the bending radius, specified in the *Special Stress Analysis* window (section 4.7.2) instead of the calculated values. D-GEO PIPELINE will not apply safety factors on those three specified values, assuming they are already included. A special stress analysis must always be started separately.

5.3 Warning and Error messages

5.3.1 Warning messages

Before calculation, warning messages might be displayed in the *Warning* window after starting the calculation. The calculation will be paused. If clicking *Yes* the calculations will continue, whereas if clicking *No* the calculations will be aborted. Figure 5.1 gives an example of warning messages displayed when an undrained layer has an undrained cohesion c_{u} of 0 and when determining the allowable curve radius in accordance with section 22.1.4.

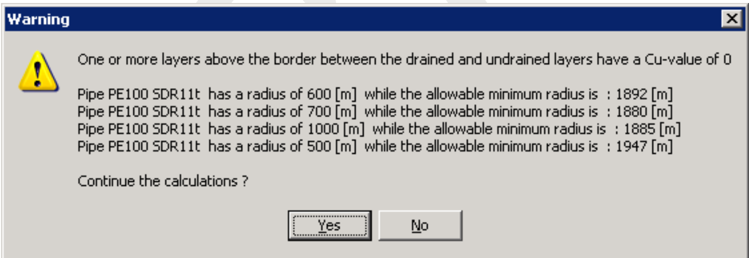


Figure 5.1: *Warning window (before calculation) about allowable radius*

5.3.2 Error messages

If errors are found in the input, no calculation can be performed and D-GEO PIPELINE opens the *Error Messages* window displaying more details about the error(s). Those errors must be corrected before performing a new calculation. To view those error messages, select the *Error Messages* option from the *Help* menu (section 3.3.1). They are also writing in the *.err file. They will be overwritten the next time a calculation is started.

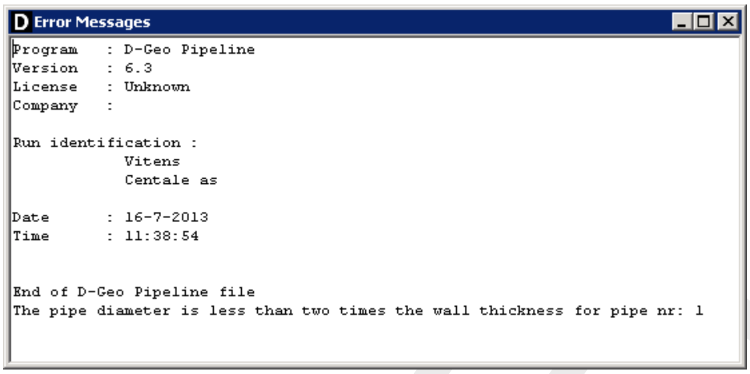


Figure 5.2: *Error Messages window*

6 View Results

6.1 Report selection

On the menu bar, click *Results* and then choose *Report Selection* to open the corresponding input window in which the content of the final report can be selected.

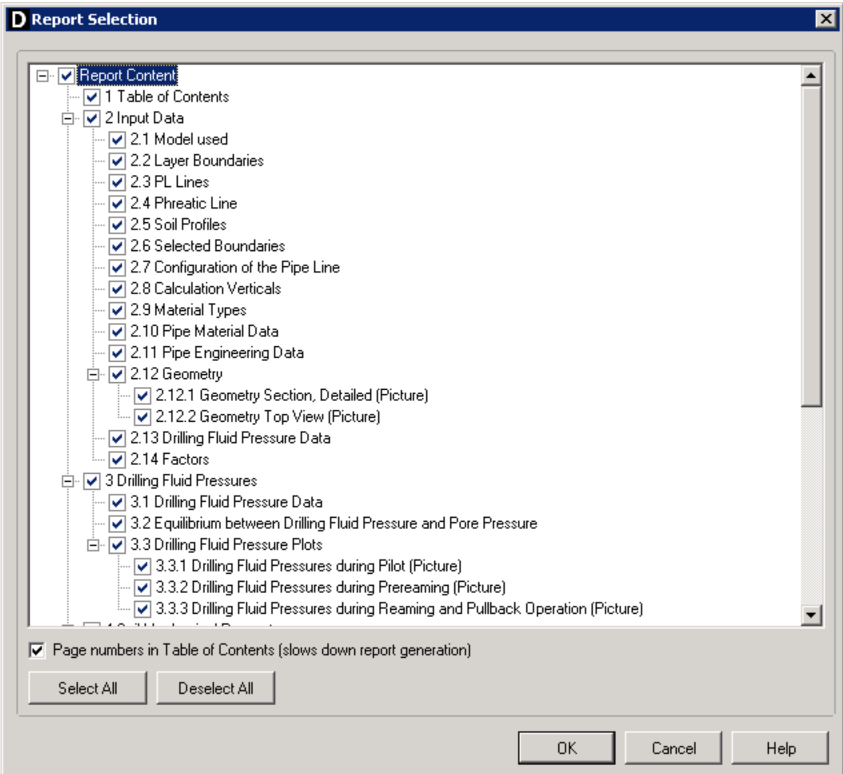


Figure 6.1: *Report Selection window*

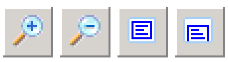
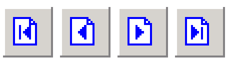
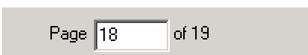
6.2 Report

On the menu bar, click *Results* and then choose *Report* to open the *Report* window displaying the selected results (section 6.1) of the calculation. This window displays the contents of the ASCII file with extension '.drd'.

Click the *Print active window* button on the icon bar to print the report.

Use the *Export Report* option in the *File* menu to export the report in RTF, PDF, TXT or HTML format.

The report has its own toolbar:

	Those four buttons enable the user to zoom in, to zoom out, to zoom the full page or to zoom the page width.
	Those four buttons enable the user to browse through the report by respectively moving to first page, moving to previous page, moving to next page or moving to last page.
	Another way of quickly browsing through the report is by entering a page number in the input field on the toolbar and pressing the *Enter* key.

The output file consists of:

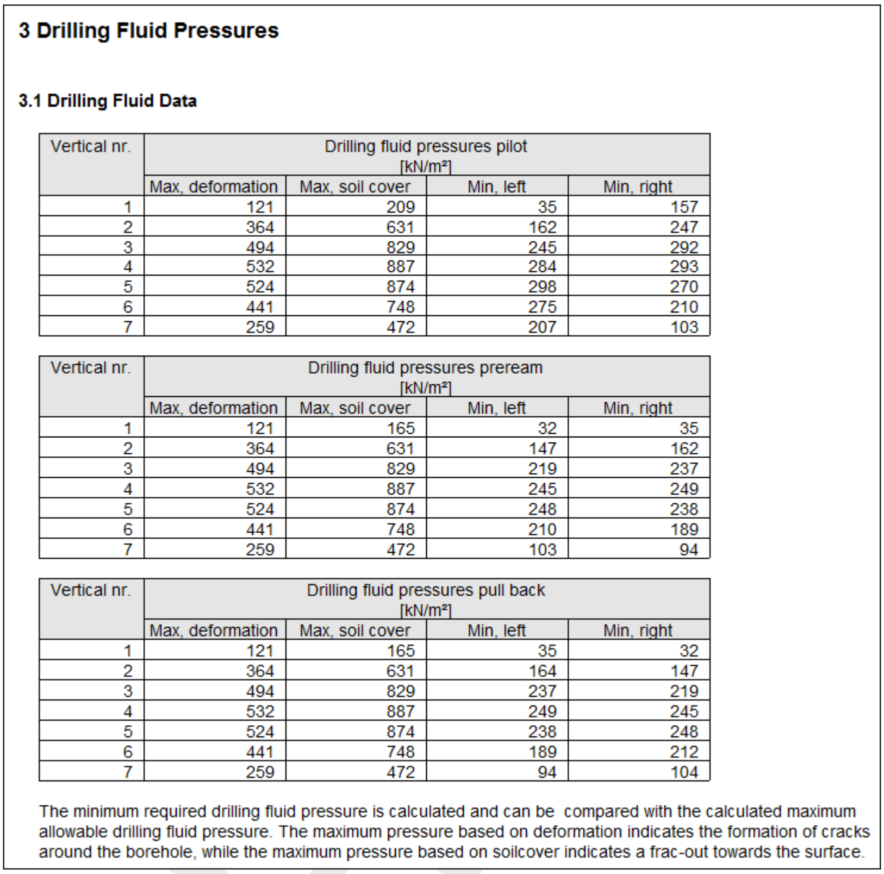
- First page
  - Date and time of report
  - File name
  - Project identification (as inputted in section 4.1.2)
- *Table of Contents*
- *Input Data* chapter gives an echo of the input
- *Drilling Fluid Pressures* chapter gives the results (plots and tables) of the drilling fluid pressures calculation for the three stages of the HDD technique (section 6.2.1)
- *Deformations* chapter gives:
  - the settlements of soil layers below the pipeline (section 6.2.2)
  - the subsidence for *Micro Tunneling* model (section 6.2.3)
- *Soil mechanical parameters* chapter which gives the soil mechanical data (section 6.2.4)
- *Data for Stress analysis* chapter includes buoyancy control and pulling forces calculation of the HDD technique (section 6.2.5)
- *Stress analysis* chapter gives the stress results for the 5 load combinations (1A, 1B, 2, 3 and 4) of the HDD technique or the Direct Pipe method (section 6.2.6)
- *Operation Parameters* chapter gives:
  - the uplift check and the hydraulic heave check for *Trenching* (section 6.2.7)
  - the uplift check, the face support pressures and the thrust forces for *Micro Tunneling* (section 6.2.8)
- *Thrust Forces* chapter gives the face support data and forces calculation of the *Direct Pipe* method (section 6.2.9)

The following sections describe the output in more detail. The calculation process can be aborted, after which a message is appended to the output file and the file is closed. All results until the moment the calculation was stopped remain in the file.

6.2.1 Report – Drilling Fluid Pressure

6.2.1.1 Report – Drilling Fluid Data

In the *Drilling Fluid Data* section, the results of the drilling fluid pressures calculation for the three stages (pilot hole drilling, pre-reaming of the borehole and pullback of the product pipe) are displayed.



3 Drilling Fluid Pressures

3.1 Drilling Fluid Data

Vertical nr.	Drilling fluid pressures pilot [kN/m²]			
	Max, deformation	Max, soil cover	Min, left	Min, right
1	121	209	35	157
2	364	631	162	247
3	494	829	245	292
4	532	887	284	293
5	524	874	298	270
6	441	748	275	210
7	259	472	207	103

Vertical nr.	Drilling fluid pressures preream [kN/m²]			
	Max, deformation	Max, soil cover	Min, left	Min, right
1	121	165	32	35
2	364	631	147	162
3	494	829	219	237
4	532	887	245	249
5	524	874	248	238
6	441	748	210	189
7	259	472	103	94

Vertical nr.	Drilling fluid pressures pull back [kN/m²]			
	Max, deformation	Max, soil cover	Min, left	Min, right
1	121	165	35	32
2	364	631	164	147
3	494	829	237	219
4	532	887	249	245
5	524	874	238	248
6	441	748	189	212
7	259	472	94	104

The minimum required drilling fluid pressure is calculated and can be compared with the calculated maximum allowable drilling fluid pressure. The maximum pressure based on deformation indicates the formation of cracks around the borehole, while the maximum pressure based on soilcover indicates a frac-out towards the surface.

Figure 6.2: *Report window, Drilling Fluid Data section*

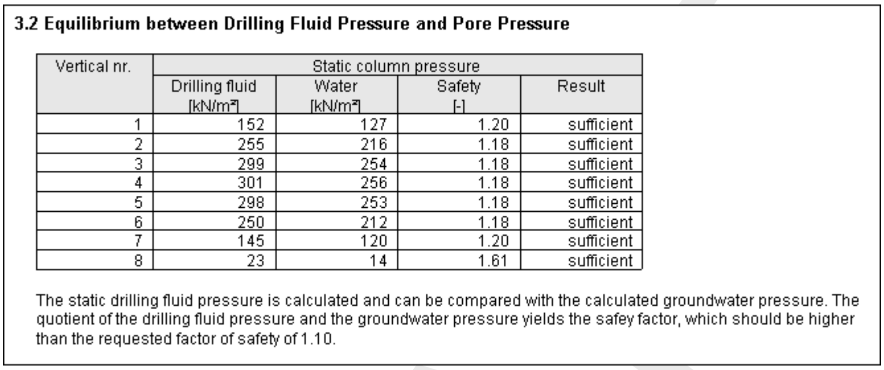
The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Max, deformation *Max, soil cover*	[kN/m^2]	Maximum drilling fluid pressure: refer to Equation 24.28 in section 24.2.2 for drained layers and to Equation 24.22 in section 24.2.1 for undrained layers. For drained layers, the determination of the maximum allowable radius of the plastic zone ($R_{\text{p;max}}$), can be related: ◇ either to the deformation of the bore hole: $R_{\text{p;max}} = \sqrt{\frac{R_{\text{b}}^2}{Q}} \times 2\varepsilon_{\text{g;max}};$ ◇ or to the soil cover: $R_{\text{p;max}} = 0.5\ H$ (Refer to section 24.2 for the definition of the parameters.)
Min,left	[kN/m^2]	Minimum drilling fluid pressure assuming that the drilling of the pilot is from left to right (see section 24.1 for background information).

Min,right	[kN/m^2]	Minimum drilling fluid pressure assuming that the drilling of the pilot is from right to left (see section 24.1 for background information).

6.2.1.2 Report – Equilibrium between Drilling Fluid Pressure and Pore Pressure

In the *Equilibrium between Drilling Fluid Pressure and Pore Pressure* section, the static drilling fluid p_1 is calculated and compared with the calculated pore pressure u, for each vertical. The ratio p_1/u yields the safety factor, which should be higher than the (user-defined) requested safety factor.



3.2 Equilibrium between Drilling Fluid Pressure and Pore Pressure

Vertical nr.	Static column pressure			
	Drilling fluid [kN/m²]	Water [kN/m²]	Safety [-]	Result
1	152	127	1.20	sufficient
2	255	216	1.18	sufficient
3	299	254	1.18	sufficient
4	301	256	1.18	sufficient
5	298	253	1.18	sufficient
6	250	212	1.18	sufficient
7	145	120	1.20	sufficient
8	23	14	1.61	sufficient

The static drilling fluid pressure is calculated and can be compared with the calculated groundwater pressure. The quotient of the drilling fluid pressure and the groundwater pressure yields the safey factor, which should be higher than the requested factor of safety of 1.10.

Figure 6.3: *Report window, Equilibrium between Drilling Fluid Pressure and Pore Pressure section*

The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Drilling fluid	[kN/m^2]	Static column pressure of the drilling fluid (p_1), see Equation 24.2 in section 24.4.
Water	[kN/m^2]	Calculated pore pressure u, see Equation 29.4 in section 29.5.
Safety	[-]	Calculated safety factor: ratio between the static drilling fluid pressure and the pore pressure.
Result		If the calculated safety factor is higher than the required safety factor, then the drilling fluid pressure is *Sufficient*, otherwise it is *Not sufficient*. **NOTE:** The required safety factor is defined in the *Factors* window under the field *Contingency factor – Pressure borehole*, see section 4.7.1.1.

6.2.2 Report – Settlements of soil layers below the pipeline

This section is available only if the *Use settlement* option in the *Model* window (section 4.1.1) has been selected before performing a calculation.

4 Deformations

4.1 Settlements of soil layers below the Pipeline

Vertical nr. [-]	Settlement [mm]	Additional settlement [mm]	dv [mm]
1	1524	5	1529
2	1483	10	1493
3	1339	20	1359
4	702	50	752
5	397	50	447
6	659	20	679
7	1473	10	1483
8	1522	5	1527

Figure 6.4: *Report window, Settlements of soil layers below the pipeline section*

The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Settlement	[mm]	Settlement calculated with the selected model, Koppejan or Isotache (section 4.1.1). For background information, see section 23.10.
Additional settlement	[mm]	Additional settlement as inputted in the *Calculation Verticals* window (section 4.4.2).
dv	[mm]	Total settlement (sum of the *Settlement* and the *Additional settlement* columns).

6.2.3 Report – Subsidence

This section is available only if the *Micro tunneling* option in the *Model* window (section 4.1.1) has been selected. Due to the overcut surface subsidence occurs. Subsidence is calculated for each vertical at different horizontal distances of the z-axis (i.e. 0 until $3\ W$, where W is the vertical distance between the surface level and the pipe center). For background information, refer to Equation 26.14 in section 26.3. Results are given in tables and in graphs.

5 Deformations

5.1 Subsidence

Due to the overcut surface, subsidence occures. The subsidence is calculated using a volume loss percentage on the overcut area. For the calculations 15.0 percent is used.

Outer diameter product pipe	1000	[mm]
Overcut on radius	200	[mm]
Volume loss	113097.3	[mm²]

5.1.2 Table of subsidence data

Vertical nr.	Subsidence in [mm] at a horizontal distance of z axe:										
	0 [mm]	0.1 W [mm]	0.2 W [mm]	0.4 W [mm]	0.7 W [mm]	1.0 W [mm]	1.3 W [mm]	1.6 W [mm]	2.0 W [mm]	2.5 W [mm]	3.0 W [mm]
1	22	21	21	20	16	12	8	5	2	0	0
2	7	7	7	6	3	1	0	0	0	0	0
3	4	4	4	3	1	0	0	0	0	0	0
4	4	4	3	3	1	0	0	0	0	0	0
5	2	2	2	1	0	0	0	0	0	0	0
6	3	3	2	2	1	0	0	0	0	0	0
7	6	6	6	4	2	1	0	0	0	0	0
8	10	10	9	8	5	2	1	0	0	0	0

Figure 6.5: *Report window, Subsidence section*

6.2.4 Report – Soil Mechanical Data

Depending on the selected model in the *Model* window section 4.1.1, the soil mechanical parameters are different.

6.2.4.1 Soil Mechanical Parameters for HDD

4 Soil Mechanical Parameters

4.1 Soil Mechanical Parameters (Pipe: 1)

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m^2
Pv;n	Neutral soil load	kN/m^2
Ph;n	Neutral horizontal soil load	kN/m^2
Pv,r;n	Reduced neutral soil load	kN/m^2
kv,top1	Vertical modulus of subgrade reaction (bilinear) upward	kN/m^3
kv,top2	Vertical modulus of subgrade reaction upward	kN/m^3
dv	Vertical displacement	mm
kv	Vertical modulus of subgrade reaction downward	kN/m^3
Pv;e	Vertical bearing capacity	kN/m^2
kh	Horizontal modulus of subgrade reaction	kN/m^3
Ph;e	Horizontal bearing capacity	kN/m^2
tmax	Maximal friction pipe-drilling fluid	kN/m^2
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m^2]	Pv;n [kN/m^2]	Ph;n [kN/m^2]	Pv,r;n [kN/m^2]	kv,top [kN/m^3]
1	24	19	12	19	253
2	74	24	16	24	188
3	582	114	35	53	3871
4	913	156	39	59	9140
5	2006	442	34	52	8287
6	1610	346	71	107	10516
7	284	155	102	155	184
8	204	83	55	83	233

Vertical nr.	dv [mm]	kv [kN/m^3]	Pv;e [kN/m^2]	kh [kN/m^3]	Ph;e [kN/m^2]	tmax [kN/m^2]	dmax [mm]
1	5	190	442	133	99	0.35	8
2	10	2365	196	1655	115	0.35	8
3	20	12208	3332	8546	794	0.35	8
4	40	13024	4449	9117	1020	0.35	8
5	80	9074	21154	6352	2006	0.35	8
6	60	7949	16672	5564	1610	0.35	8
7	50	309	1233	216	284	0.35	8
8	35	166	831	116	211	0.35	8

Maximum soil load	:	Pv;n, max = 442 kN/m^2
Maximum reduced soil load	:	Pv,r;n, max = 155 kN/m^2
Maximum vertical modulus of subgrade reaction (without safety factor)	:	kv, max = 13024 kN/m^3
Maximum vertical modulus of subgrade reaction (with safety factor)	:	kv, max = 20468 kN/m^3

Figure 6.6: *Report window – Soil Mechanical Parameters section (for HDD)*

The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Pv;p	[kN/m^2]	Passive soil load (see Equation 23.2 in section 23.2).
Pv;n	[kN/m^2]	Neutral vertical soil load (see Equation 23.1 in section 23.1).
Ph;n	[kN/m^2]	Neutral horizontal soil load (see Equation 23.12 in section 23.5.1).
Pv,r;n	[kN/m^2]	Reduced neutral soil load (see Equation 23.4 and Equation 23.8 in section 23.3).
kv;top	[kN/m^3]	Vertical modulus of subgrade reaction at the top of the pipe (see Equation 23.14 in section 23.6.1).
dv	[mm]	Vertical displacement (see section 23.10).
kv	[kN/m^3]	Vertical modulus of subgrade reaction at the bottom of the pipe (see Equation 23.14 in section 23.6.1).
Pv;e	[kN/m^2]	Vertical bearing capacity (see Equation 23.26 in section 23.8).
kh	[kN/m^3]	Horizontal modulus of subgrade reaction (see Equation 23.24 in section 23.7.1).

Ph;e	[kN/m^2]	Horizontal bearing capacity (see Equation 23.28 in section 23.9.1).
tmax	[kN/m^2]	Maximal axial friction along the pipeline (see section 23.11.1).
dmax	[mm]	Displacement necessary to develop the maximal axial friction along the pipeline (see section 23.12.1).

6.2.4.2 Soil Mechanical Parameters for Micro tunneling

3 Soil Mechanical Data

3.1 Soil Mechanical Parameters

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m²
Pv;n	Neutral soil load	kN/m²
Ph;n	Neutral horizontal soil load	kN/m²
Pv,r;n	Reduced neutral soil load	kN/m²
kv,top1	Vertical modulus of subgrade reaction (bilinear) upward	kN/m³
kv,top2	Vertical modulus of subgrade reaction upward	kN/m³
dv	Vertical displacement	mm
kv	Vertical modulus of subgrade reaction downward	kN/m³
Pv;e	Vertical bearing capacity	kN/m²
kh	Horizontal modulus of subgrade reaction	kN/m³
Ph;e	Horizontal bearing capacity	kN/m²
tmax	Maximal friction along pipe	kN/m²
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m²]	Pv;n [kN/m²]	Ph;n [kN/m²]	Pv,r;n [kN/m²]	kv,top [kN/m³]
1	24	19	14	19	253
2	74	24	18	24	188
3	582	114	57	61	3871
4	913	156	78	76	9140
5	2006	442	188	75	8287
6	1610	346	148	148	10516
7	284	155	115	155	184
8	204	83	62	83	233

Vertical nr.	dv [mm]	kv [kN/m³]	Pv;e [kN/m²]	kh [kN/m³]	Ph;e [kN/m²]	tmax [kN/m²]	dmax [mm]	mat [-]
1	5	190	442	133	184	12.55	12	Peat
2	10	2365	196	1655	93	12.40	12	Peat
3	20	12208	3332	8546	1507	16.39	5	Clay
4	40	13024	4449	9117	2177	18.32	5	Clay
5	80	9074	21154	6352	11957	22.72	2	Sand
6	60	7949	16672	5564	6609	25.79	2	Sand
7	50	309	1233	216	533	26.56	12	Peat
8	35	166	831	116	419	19.30	12	Peat

Maximum soil load	:	Pv;n, max = 442 kN/m²
Maximum reduced soil load	:	Pv,r;n, max = 155 kN/m²
Maximum vertical modulus of subgrade reaction (without safety factor)	:	kv, max = 13024 kN/m³
Maximum vertical modulus of subgrade reaction (with safety factor)	:	kv, max = 20468 kN/m³

Figure 6.7: *Report window – Soil Mechanical Parameters section (for Micro tunneling)*

The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Pv;p	[kN/m^2]	Passive soil load (see Equation 23.2 in section 23.2).
Pv;n	[kN/m^2]	Neutral vertical soil load (see Equation 23.1 in section 23.1).
Ph;n	[kN/m^2]	Neutral horizontal soil load (see Equation 23.13 in section 23.5.2).
Pv,r;n	[kN/m^2]	Reduced neutral soil load (see section 23.3).
kv;top	[kN/m^3]	Vertical modulus of subgrade reaction upward (see Equation 23.14 in section 23.6.1).
dv	[mm]	Vertical displacement (see section 23.10).

kv	[kN/m^3]	Vertical modulus of subgrade reaction downward (see Equation 23.14 in section 23.6.1).
Pv;e	[kN/m^2]	Vertical bearing capacity (see Equation 23.26 in section 23.8).
kh	[kN/m^3]	Horizontal modulus of subgrade reaction (see Equation 23.24 in section 23.7.1).
Ph;e	[kN/m^2]	Horizontal bearing capacity (see Equation 23.29 in section 23.9.2).
tmax	[kN/m^2]	Maximal axial friction along the pipeline (see Equation 23.52 in section 23.11.2).
dmax	[mm]	Displacement at maximal friction (see section 23.12.2).
mat	[-]	The corresponding type of material (see section 23.13).

6.2.4.3 Soil Mechanical Parameters for Construction in trench

3 Soil Mechanical Data

3.1 Soil Mechanical Parameters

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m²
Pv;n	Neutral soil load	kN/m²
Ph;n	Neutral horizontal soil load	kN/m²
Pv;a	Actual soil load	kN/m²
kv,top1	Vertical modulus of subgrade reaction (bilinear) upward	kN/m³
kv,top2	Vertical modulus of subgrade reaction upward	kN/m³
dv	Vertical displacement	mm
kv1	Vertical modulus of subgrade reaction downward, first branch	kN/m³
kv2	Vertical modulus of subgrade reaction downward, second branch	kN/m³
Pv;e	Vertical bearing capacity	kN/m²
kh	Horizontal modulus of subgrade reaction	kN/m³
Ph;e	Horizontal bearing capacity	kN/m²
tmax	Maximal friction along pipe	kN/m²
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m²]	Pv;n [kN/m²]	Ph;n [kN/m²]	Pv;a [kN/m²]	kv,top1 [kN/m²]	kv,top2 [kN/m³]
1	1	1	0	1	1	6
2	9	5	4	6	37	85
3	99	31	13	99	158781	2.31E+05
4	95	23	12	95	129743	1.72E+05
5	23	13	13	16	76	170
6	10	8	6	8	12	57

Vertical nr.	dv [mm]	kv1 [kN/m³]	kv2 [kN/m³]	Pv;e [kN/m²]	kh [kN/m³]	Ph;e [kN/m²]	tmax [kN/m²]	dmax [mm]	mat [-]
1	5	1621	324	64	2970	36	24	12	Peat
2	10	7876	1575	261	3699	59	7	15	Peat
3	20	39240	7848	1622	15130	448	13	2	Sand
4	80	31186	6237	733	10301	234	10	5	Clay
5	50	813	163	52	1217	23	14	15	Peat
6	35	3692	591	363	4095	53	26	12	Peat

Figure 6.8: *Report window – Soil Mechanical Parameters section (for Construction in trench)*

The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Pv;p	[kN/m^2]	Passive soil load (see Equation 23.2 in section 23.2).
Pv;n	[kN/m^2]	Neutral vertical soil load (see Equation 23.1 in section 23.1).
Ph;n	[kN/m^2]	Neutral horizontal soil load (see Equation 23.13 in section 23.5.2).
Pv;a	[kN/m^2]	Initial soil load, also called actual soil load (see Equation 23.9 in section 23.4).

kv;top1	[kN/m^3]	Vertical modulus of subgrade reaction upward (see section 23.6.2).
kv;top2	[kN/m^3]	Vertical modulus of subgrade reaction upward (see section 23.6.2).
dv	[mm]	Vertical displacement (see section 23.10).
kv1	[kN/m^3]	Vertical modulus of subgrade reaction downward of the first and second branch (see section 23.6.2).
kv2	[kN/m^3]	Vertical modulus of subgrade reaction downward of the first and second branch (see section 23.6.2).
Pv;e	[kN/m^2]	Vertical bearing capacity (see Equation 23.26 in section 23.8).
kh	[kN/m^3]	Horizontal modulus of subgrade reaction (see Equation 23.25 in section 23.7.2).
Ph;e	[kN/m^2]	Horizontal bearing capacity (see Equation 23.29 in section 23.9.2).
tmax	[kN/m^2]	Maximal axial friction along the pipeline (see Equation 23.52 in section 23.11.2).
dmax	[mm]	Displacement at maximal friction (see section 23.12.2).
mat	[-]	The corresponding type of material (see section 23.13).

6.2.4.4 Soil Mechanical Parameters for Direct Pipe

4 Soil Mechanical Parameters

4.1 Soil Mechanical Parameters (Pipe: 1)

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m²
Pv;n	Neutral soil load	kN/m²
Ph;n	Neutral horizontal soil load	kN/m²
Pv,r;n	Reduced neutral soil load	kN/m²
kv,top1	Vertical modulus of subgrade reaction (bilinear) upward	kN/m³
kv,top2	Vertical modulus of subgrade reaction upward	kN/m³
dv	Vertical displacement	mm
kv	Vertical modulus of subgrade reaction downward	kN/m³
Pv;e	Vertical bearing capacity	kN/m²
kh	Horizontal modulus of subgrade reaction	kN/m³
Ph;e	Horizontal bearing capacity	kN/m²
tmax	Maximal friction pipe-drilling fluid	kN/m²
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m²]	Pv;n [kN/m²]	Ph;n [kN/m²]	Pv,r;n [kN/m²]	kv,top [kN/m³]
1	24	19	12	19	253
2	74	24	16	24	188
3	582	114	35	53	3871
4	913	156	39	59	9140
5	2006	442	34	52	8287
6	1610	346	71	107	10516
7	284	155	102	155	184
8	204	83	55	83	233

Vertical nr.	dv [mm]	kv [kN/m³]	Pv;e [kN/m²]	kh [kN/m³]	Ph;e [kN/m²]	tmax [kN/m²]	dmax [mm]
1	5	190	442	133	99	0.35	8
2	10	2365	196	1655	115	0.35	8
3	20	12208	3332	8546	794	0.35	8
4	40	13024	4449	9117	1020	0.35	8
5	80	9074	21154	6352	2006	0.35	8
6	60	7949	16672	5564	1610	0.35	8
7	50	309	1233	216	284	0.35	8
8	35	166	831	116	211	0.35	8

Maximum soil load	:	Pv;n, max = 442 kN/m²
Maximum reduced soil load	:	Pv,r;n, max = 155 kN/m²
Maximum vertical modulus of subgrade reaction (without safety factor)	:	kv, max = 13024 kN/m³
Maximum vertical modulus of subgrade reaction (with safety factor)	:	kv, max = 20468 kN/m³

Figure 6.9: *Report window – Soil Mechanical Parameters section (for Direct Pipe)*

The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Pv;p	[kN/m^2]	Passive soil load (see Equation 23.2 in section 23.2).
Pv;n	[kN/m^2]	Neutral vertical soil load (see Equation 23.1 in section 23.1).
Ph;n	[kN/m^2]	Neutral horizontal soil load (see Equation 23.12 in section 23.5.1).
Pv,r;n	[kN/m^2]	Reduced neutral soil load (see Equation 23.4 and Equation 23.8 in section 23.3).
kv;top	[kN/m^3]	Vertical modulus of subgrade reaction at the top of the pipe (see Equation 23.14 in section 23.6.1).
dv	[mm]	Vertical displacement (see section 23.10).
kv	[kN/m^3]	Vertical modulus of subgrade reaction at the bottom of the pipe (see Equation 23.14 in section 23.6.1).
Pv;e	[kN/m^2]	Vertical bearing capacity (see Equation 23.26 in section 23.8).
kh	[kN/m^3]	Horizontal modulus of subgrade reaction (see Equation 23.24 in section 23.7.1).

Ph;e	[kN/m^2]	Horizontal bearing capacity (see Equation 23.28 in section 23.9.1).
tmax	[kN/m^2]	Maximal axial friction along the pipeline (see section 23.11.1).
dmax	[mm]	Displacement necessary to develop the maximal axial friction along the pipeline (see section 23.12.1).

6.2.5 Report – Data for Stress Analysis

Buoyancy Control

The magnitude of the pulling force is caused in part by friction between the soil around the borehole and the product pipe. In turn, the magnitude of the friction is dependent on the degree of buoyancy of the pipeline in the drilling fluid. Uplift forces resulting from buoyancy can be neutralized by filling the pipeline with water. The optimum volume of water placed in the pipeline provides the most advantageous distribution of buoyant forces. If the resulting force is a positive value, the pipeline will move upwards. If the resulting force is a negative value the pipeline will move downwards.

5.2 Buoyancy Control

The friction between soil and pipe is partially caused by buoyancy of the pipeline in the drilling fluid. Uplift forces resulting from buoyancy can be neutralized by filling the pipeline. The optimal volume of water placed in the pipe provides the most advantageous distribution of buoyant forces.

Buoyancy of the pipeline when filled with water for 15%

Uplift forces	:	2297	[kg/m]	
Weight of pipeline (including filling)	:	1288	[kg/m]	

Result	:	1009	[kg/m]	(Pipeline moves upwards)

Figure 6.10: *Report window, Buoyancy Control section*

The following is an explanation of the content:

Uplift forces	Weight of the drilling fluid in kg/m (see Equation 25.1 in section 25.1).
Weight of pipeline (including filling)	Weight of the pipeline filled with water in kg/m (see Equation 25.4 in section 25.1).
Resulting	Effective weight of the pipeline in kg/m (see Equation 25.5 in section 25.1).

See section 25.1 for background information on buoyancy control.

Calculation pulling forces

This part of the report displays the calculated pulling forces (without applying a contingency factor), for characteristic locations along the drilling line. In a case without horizontal bending, six characteristic points are calculated. Their location is given in Figure 6.12. In case of horizontal bending, the beginning and ending points of each horizontal bending will be defined as characteristic points.

5.3 Calculation Pulling Force

During the pullback operation the pipe experiences friction which is based on:

- friction between pipe and pipe-roller (f1 = 0.20)
- friction between pipe and drilling fluid (f2 = 0.000350 [N/mm²])
- friction between pipe and soil (f3 = 0.30)

Due to the friction a pulling force is induced in the pipeline.
The pulling direction of the product pipe is from left to right

This calculation takes into account that the length of the pipe on the rollers decreases while pulling back the pipeline. During the pull back operation the bore hole is supposed to be stable.

Characteristic points	Length pipe in bore hole (m)	Expected pulling force (kN)
T1	0	4610
T2	43	4701
T3	338	6579
T4	1441	14235
T5	1716	16676
T6	1790	16832

The calculated pulling force is the mean value. It is recommended to use a contingency factor of at least 1.4 for the stress analysis. In the subsequent pipe stress analysis a factor of 0.00 is used and a load factor of 1.20 (steel only).

The maximum representative pulling force is 0 kN, calculation factor excluded. At this pulling force level the stresses in the pipeline are equal to the yield strength.

Figure 6.11: *Report window, Calculation pulling force section*

The following is an explanation of the column headings:

Characteristic points	Points at different locations along the drilling line (see Figure 6.12). T1 and T6 are the entry and exit points, respectively.
Length pipe in borehole	Length of the pipe between the entry point and the characteristic point.
Expected pulling force	Calculated pulling forces without using a contingency factor (see Equation 25.6 in section 25.2).

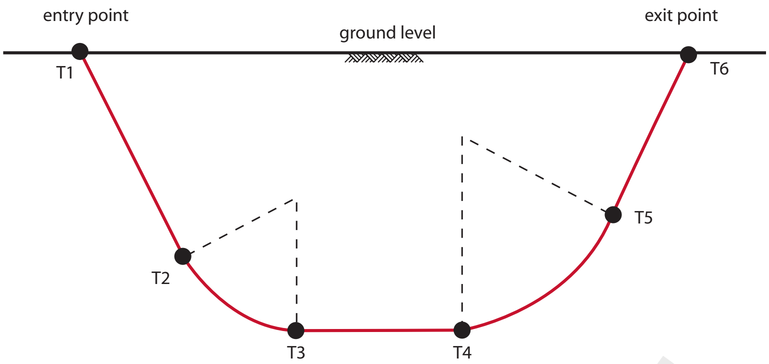


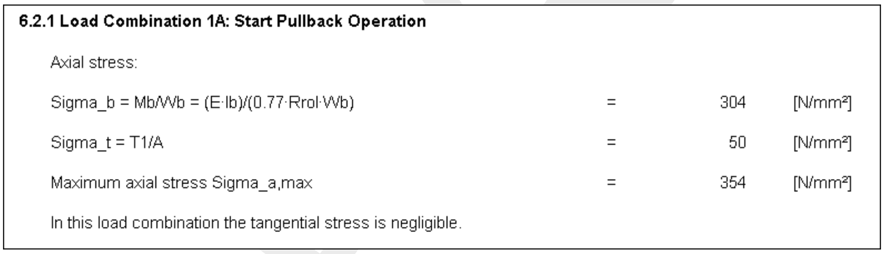
Figure 6.12: *Locations of the characteristic points T1 to T6*

6.2.6 Report – Stress Analysis

6.2.6.1 Stress Analysis HDD

Load Combination 1A: Start pull-back operation

This part of the report displays the calculated axial and tangential stresses at the start of the pull-back operation. See section 25.5.1 for background information.



6.2.1 Load Combination 1A: Start Pullback Operation

Axial stress:

Sigma_b = Mb/Wb = (E·Ib)/(0.77·Rrol·Wb)	=	304	[N/mm²]
Sigma_t = T1/A	=	50	[N/mm²]
Maximum axial stress Sigma_a,max	=	354	[N/mm²]

In this load combination the tangential stress is negligible.

Figure 6.13: *Report window, Stress analysis for load combination 1A*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.23.
Sigma_t	Axial stress due to friction of the pipeline on the roller-lane, in N/mm^2, see Equation 25.25.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.26.

Load Combination 1B: End pull-back operation

This part of the report displays the calculated axial and tangential stresses at the end of the pullback operation. See section 25.5.2 for background information.

6.2.2 Load Combination 1B: End Pullback Operation

Axial stress:			
Sigma_b = Mb/Wb = (E·Ib)/(0.77·Rmin·Wb)	=	347	N/mm²
Sigma_t = Tmax/A	=	183	N/mm²
Maximum axial stress Sigma_a,max	=	530	N/mm²
Tangential stress:			
Load qr on pipeline due to reaction of soil in bends (according to NEN 3650-1 annex 5 D3.3):			
qr = kv·Y = (0.322·Lambda^2·E·I)/(0.77.Do.R)			
Lambda = (kv·Do/(4·E·I))^0.25	=	1.8E-4	mm-1
qr	=	0.0977	N/mm²
Sigma_qr = k'·qr·(rg/Ww)·Do	=	39	N/mm²
Maximum tangential stress Sigma_t,max	=	39	N/mm²

Figure 6.14: *Report window, Stress analysis for load combination 1B*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.27.
Sigma_t	Axial stress due to pull-back in N/mm^2, see Equation 25.28.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.29.
Lambda	Characteristic stiffness between the pipeline and the soil in mm^{-1}, see Equation 25.13.
qr	Soil reaction in N/mm^2, see Equation 25.11.
Sigma_qr	Stress due to soil reaction in N/mm^2, see Equation 25.31.
Sigma_t,max	Maximum tangential stress in N/mm^2, see Equation 25.32.

Load Combination 2: Application internal pressure

This part of the report displays the calculated stresses when the internal pressure is applied. See section 25.5.3 for background information.

6.2.3 Load Combination 2: Application Internal Pressure

Due to internal pressure :			
Sigma_py = pd·(Do - t)/(2·t)	=	15	N/mm²
Sigma_px = 0.5·Sigma_py	=	8	N/mm²
Sigma_ptest = sf.pt·(Do - t)/(2·t)	=	23	N/mm²

Figure 6.15: *Report window, Stress analysis for load combination 2*

Sigma_py	Internal stress due to design pressure in N/mm^2, see Equation 25.33 for thin pipe and Equation 25.35 for thick pipe.
Sigma_px	Internal axial stress due to design pressure in N/mm^2, see Equation 25.37.
Sigma_ptest	Internal stress due to test pressure in N/mm^2, see Equation 25.34 for thin pipe and Equation 25.36 for thick pipe.

Load Combination 3: In operation (situation without pressure)

This part of the report displays the calculated axial and tangential stresses when the pipe is in operation without internal pressure. See section 25.5.4 for background information.

6.2.4 Load Combination 3: In Operation (Situation without Pressure)

Axial stress:			
Sigma_b = Mb/Wb = (E·Ib)/(0.77·Rmin·Wb)	=	347	N/mm²
Maximum axial stress Sigma_a,max	=	347	N/mm²
Tangential stress:			
Sigma_qr = k'·qr·(rg/Ww)·Do	=	39	N/mm²
Sigma_qn = k·qn·(rg/Ww)·Do	=	182	N/mm²
Maximum tangential stress Sigma_t,max	=	220	N/mm²

Figure 6.16: *Report window – Stress analysis for load combination 3*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.38.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.39.
Sigma_qr	Stress due to soil reaction in N/mm^2, see Equation 25.40.
Sigma_qn	Stress due to reduced vertical load in N/mm^2, see Equation 25.41.
Sigma_t,max	Maximum tangential stress in N/mm^2, see Equation 25.42.

Load Combination 4: In operation (with internal pressure)

This part of the report displays the calculated axial and tangential stresses when the pipe is in operation with internal pressure. See section 25.5.5 for background information.

6.2.3 Load Combination 4: In Operation (with Internal Pressure)

Axial stress:			
Sigma_b = Mb/Wb = (E·Ib)/(0.77·Rrol·Wb)	=	347	N/mm²
Due to internal pressure :			
Sigma_py = pd·(Do - t)/(2·t)	=	18	N/mm²
Sigma_px = 0.5·Sigma_py	=	9	N/mm²
Sigma_ptest = sf.pt·(Do - t)/(2·t)	=	23	N/mm²
Sigma_Temp = Dt * gamma_t * alpha g * E	=	15	N/mm²
Maximum axial stress Sigma_a,max	=	371	N/mm²
Tangential stress:			
Sigma_qr = k'·qr·(rg/Ww)·Do	=	39	N/mm²
Sigma_qn = k·qn·(rg/Ww)·Do	=	182	N/mm²
Rerounding factor Frr	=	0.947	
Rerounding factor F'rr	=	0.974	
Sigma_t,max = Sigma_py + ((F'rr·Sigma_qr) + (Frr·Sigma_qn))			
Maximum tangential stress Sigma_t,max	=	228	N/mm²

Figure 6.17: *Report window, Stress analysis for load combination 4*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.43.
Sigma_py	Ring stress due to internal design pressure in N/mm^2, see Equation 25.44.

Sigma_px	Axial stress due to internal design pressure in N/mm^2, see Equation 25.47.
Sigma_ptest	Ring stress due to internal test pressure in N/mm^2, see Equation 25.45 for steel and Equation 25.46 for PE.
Sigma_Temp	Axial stress due to temperature variation in N/mm^2, see Equation 25.48.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.49.
Sigma_qr	Stress due to soil reaction in N/mm^2, see Equation 25.50.
Sigma_qn	Stress due to reduced vertical load in N/mm^2, see Equation 25.51.
Frr	Direct re-rounding factor in N/mm^2, see Equation 25.53.
Frr'	Indirect re-rounding factor in N/mm^2, see Equation 25.54.
Sigma_t,max	Maximum tangential stress in N/mm^2, see Equation 25.52.

Check on calculated stresses (Steel)

This part of the report displays a table in which the calculated combined stresses of the different load combinations are compared to the maximum allowable stress (see section 25.6.1.1 for background information).

6.3 Check on Calculated StressesPipe: 1

According to NEN 3650-2 art.5 D.3.1 the calculated stresses for the load combinations, must meet the following conditions (note: Re = 200 [N/mm²]) :

Load combinations 1, 3 and 4
- Sigma_vmax =< 0.85(Re+Re_20deg)/Gamma_m

Load combination 2
- Sigma_ptest =< Re/Gamma_test
- Sigma_py =< Re/Gamma_m
- Sigma_pm =< 1.1·Re/Gamma_m

In load combination 1A/1B/3/4 stresses are NOT allowable.

	Max allowable stress [N/mm²]	Load combination1A	Load combination1B	Load combination2	Load combination3	Load combination4
Sigma_ptest	173.91	-	-	23	-	-
Sigma_py	153.85	-	-	15	-	-
Sigma_pm	169.23	-	-	13	-	-
Sigma_vmax	261.54	354	550	-	495	486

Stresses in pipeline [N/mm²]

Figure 6.18: *Report window, Check on calculated stresses section (steel pipe)*

Check on calculated stresses (PE)

This part of the report displays a table in which the calculated combined stresses of the different load combinations are compared to the maximum allowable stress (see section 25.6.1.2 for background information).

6.3 Check on Calculated StressesPipe: 1

Load combination 1
- Sigma_AxMax < ShortStrength * DamageFactor
- Sigma_TanMax < ShortStrength * DamageFactor

Load combination 2
- Sigma_ptest < ShortStrength * DamageFactor
- Sigma_py < LongStrength * DamageFactor

Load combination 3
- Sigma_AxMax < LongStrength * DamageFactor
- Sigma_TanMax < LongStrength * DamageFactor

Load combination 4
- Sigma_AxMax < LongStrength * DamageFactor
- Sigma_TanMax < LongStrength * DamageFactor

In load combination 1B stresses are NOT allowable.

	Max allowable stress [N/mm^2]	Load combination1A	Load combination1B	Load combination2	Load combination3	Load combination4
Sigma_ptest	6.40 (short)	-	-	4.5	-	-
Sigma_py	5.04 (long)	-	-	2.5	-	-
Sigma_axial	6.40 (short)	5.0	221.0	-	-	-
Sigma_axial	5.04 (long)	-	-	-	0.0	1.3
Sigma_tang...	6.40 (short)	-	0.0	-	-	-
Sigma_tang...	5.04 (long)	-	-	-	2.5	4.2

Stresses in pipeline [N/mm^2]

Figure 6.19: *Report window, Check on calculated stresses section (PE pipe)*

Check on deflection

This part of the report displays the calculated deflection of the pipeline and compares it to the maximum allowable deflection (see section 25.7 for background information).

The deflection of the pipeline is 0.8 mm (1.6% x Do). The maximum allowable deflection of the pipeline is 4.0 mm (10.0% x S x Do). The deflection is allowable.
For piggability the maximum allowable deflection of the pipeline is 3.5 mm (7.0% x Do). The deflection is allowable..

Figure 6.20: *Report window, Check on deflection section*

Check for implosion (only for PE pipe)

This calculation is performed only for a polyethylene pipe. The maximum allowable external pressure is calculated (see section 25.8 for background information) in the short and long term for the pullback operation (Stage 2) and the pipeline in operation (Stage 3a), respectively.

6.3.4 Check for ImplosionPipe: 1

During the pullback operation the drilling fluid gives an external pressure. The highest minimum required drilling fluid pressure during the pullback operation is 594 kN/m^2, this is less than the maximum allowable external pressure of 1022 kN/m^2.

If the pipe is completely filled during the pullback operation the fluid gives an internal pressure of 520 kN/m^2. This taken in account the total allowable pressure becomes 1542 kN/m^2. This is more than the maximum external pressure.

In operation the water pressure at the lowest point of the drilling gives an external pressure. The maximum water pressure equals 352 kN/m^2, this is more than the maximum allowable external pressure of 186 kN/m^2.

If the pipe stays completely filled during operation, the fluid gives an internal pressure of 520 kN/m^2. This taken in account the total allowable pressure becomes 706 kN/m^2. This is more than the maximum external pressure.

Figure 6.21: *Report window, Check for implosion section*

6.2.6.2 Stress Analysis Direct Pipe

Load combination 1A: Start Thrust Operation

This part of the report describes the axial and the tangential stresses at the start of the thrust operation.

5.2.1 Load Combination 1A: Start Thrust Operation

Axial stress:

Sigma_b = Mb/Wb = 1.15·1.10·(E·Ib)/(0.91·Rrol·Wb)	=	17468613	[N/mm²]
Sigma_t = f_pull * T1/A	=	16	[N/mm²]
Maximum axial stress Sigma_a,max	=	17468628	[N/mm²]

In this load combination the tangential stress is negligible.

Figure 6.22: *Report window, Stress analysis for load combination 1A*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.23.
Sigma_t	Axial stress due to friction of the pipeline on the roller-lane, in N/mm^2, see Equation 25.25.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.26.

Load Combination 1B: Maximum Thrust

This part of the report displays the calculated axial and tangential stresses at the maximum thrust. See section 25.5.2 for background information.

5.2.2 Load Combination 1B: Maximum Thrust

Axial stress:

Sigma_b = Mb/Wb = 1.15·1.10·(E·Ib)/(0.91·Rmin·Wb)	=	125	N/mm²
Sigma_t = f_pull * Tmax/A	=	48	N/mm²
Maximum axial stress Sigma_a,max	=	172	N/mm²

Tangential stress:

Load qr on pipeline due to reaction of soil in bends (according to NEN 3650-1 annex 5 D3.3):

qr = kv·Y = (0.322·Lambda^2·E·I)/(1.10.Do.R)			
Lambda = (kv·Do/(4·E·I))^0.25	=	1.6E-4	mm-1
qr	=	0.05069	N/mm²
Load qbuc on pipeline due to buckling :			
N = (L^2.F/(3·E·I.pi^2))^0.5 + 1	=	3.833	
qbuc = 4.N.F.Gap/(A.L)	=	0.033433	N/mm²
qtot = qr + qbuc			
Sigma_qr = k'·qtot·(rg/Ww)·Do	=	34	N/mm²
Maximum tangential stress Sigma_t,max	=	34	N/mm²

Figure 6.23: *Report window, Stress analysis for load combination 1B*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.27.
Sigma_t	Axial stress due to pull-back in N/mm^2, see Equation 25.28.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.29.

Lambda	Characteristic stiffness between the pipeline and the soil in mm^{-1}, see Equation 25.13.
qr	Soil reaction in N/mm^2, see Equation 25.11.
N	??.
qbuc	Additional friction caused by buckling in N/mm^2
Sigma_qr	Stress due to soil reaction in N/mm^2, see Equation 25.31.
Sigma_t,max	Maximum tangential stress in N/mm^2, see Equation 25.32.

Load Combination 2: Application internal pressure

This part of the report displays the calculated stresses when the internal pressure is applied. See section 25.5.3 for background information.

5.2.3 Load Combination 2: Application Internal Pressure

Due to internal pressure :

Sigma_py = pd·(Do - t)/(2·t)	=	258	N/mm²
Sigma_px = 0.5·Sigma_py	=	129	N/mm²
Sigma_ptest = sf.pt·(Do - t)/(2·t)	=	0	N/mm²

Figure 6.24: *Report window, Stress analysis for load combination 2*

Sigma_py	Internal stress due to design pressure in N/mm^2, see Equation 25.33 for thin pipe and Equation 25.35 for thick pipe.
Sigma_px	Internal axial stress due to design pressure in N/mm^2, see Equation 25.37.
Sigma_ptest	Internal stress due to test pressure in N/mm^2, see Equation 25.34 for thin pipe and Equation 25.36 for thick pipe.

Load Combination 3: In operation (situation without pressure)

This part of the report displays the calculated axial and tangential stresses when the pipe is in operation without internal pressure. See section 25.5.4 for background information.

5.2.4 Load Combination 3: In Operation (Situation without Pressure)

Axial stress:

Sigma_b = Mb/Wb = 1.15·1.10·(E·Ib)/(0.91·Rrol·Wb)	=	125	N/mm²
Maximum axial stress Sigma_a,max	=	125	N/mm²

Tangential stress:

Sigma_qr = k'·qr·(rg/Ww)·Do	=	34	N/mm²
Sigma_qn = k·qn·(rg/Ww)·Do	=	410	N/mm²
Maximum tangential stress Sigma_t,max	=	445	N/mm²

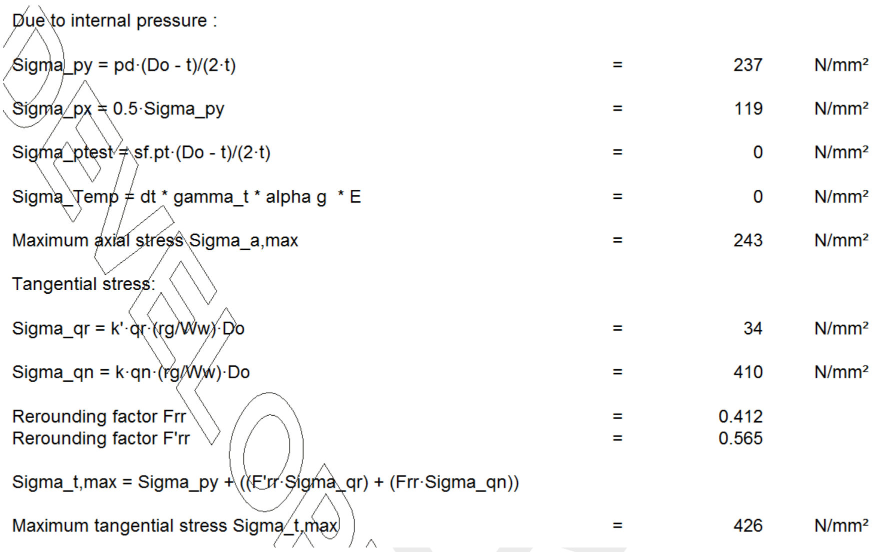
Figure 6.25: *Report window – Stress analysis for load combination 3*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.38.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.39.
Sigma_qr	Stress due to soil reaction in N/mm^2, see Equation 25.40.

Sigma_qn	Stress due to reduced vertical load in N/mm^2, see Equation 25.41.
Sigma_t,max	Maximum tangential stress in N/mm^2, see Equation 25.42.

Load Combination 4: In operation (with internal pressure)

This part of the report displays the calculated axial and tangential stresses when the pipe is in operation with internal pressure. See section 25.5.5 for background information.



Due to internal pressure :

Sigma_py = pd·(Do - t)/(2·t)	=	237	N/mm²
Sigma_px = 0.5·Sigma_py	=	119	N/mm²
Sigma_ptest = sf.pt·(Do - t)/(2·t)	=	0	N/mm²
Sigma_Temp = dt * gamma_t * alpha g * E	=	0	N/mm²
Maximum axial stress Sigma_a,max	=	243	N/mm²
Tangential stress:			
Sigma_qr = k'·qr·(rg/Ww)·Do	=	34	N/mm²
Sigma_qn = k·qn·(rg/Ww)·Do	=	410	N/mm²
Rerounding factor Frr	=	0.412	
Rerounding factor F'rr	=	0.565	
Sigma_t,max = Sigma_py + ((F'rr·Sigma_qr) + (Frr·Sigma_qn))			
Maximum tangential stress Sigma_t,max	=	426	N/mm²

Figure 6.26: *Report window, Stress analysis for load combination 4*

Sigma_b	Axial bending stress in N/mm^2, see Equation 25.43.
Sigma_py	Ring stress due to internal design pressure in N/mm^2, see Equation 25.44.
Sigma_px	Axial stress due to internal design pressure in N/mm^2, see Equation 25.47.
Sigma_ptest	Ring stress due to internal test pressure in N/mm^2, see Equation 25.45 for steel and Equation 25.46 for PE.
Sigma_Temp	Axial stress due to temperature variation in N/mm^2, see Equation 25.48.
Sigma_a,max	Maximum axial stress in N/mm^2, see Equation 25.49.
Sigma_qr	Stress due to soil reaction in N/mm^2, see Equation 25.50.
Sigma_qn	Stress due to reduced vertical load in N/mm^2, see Equation 25.51.
Frr	Direct re-rounding factor in N/mm^2, see Equation 25.53.
F'rr	Indirect re-rounding factor in N/mm^2, see Equation 25.54.
Sigma_t,max	Maximum tangential stress in N/mm^2, see Equation 25.52.

6.2.7 Report – Operation Parameters (Trenching)

Uplift Check

Due to buoyancy of an empty pipeline below the groundwater table, the uplift should be checked. Results are given per vertical in a table (Figure 6.27) and in graphs.

4.1 Uplift Check

Due to buoyancy of the pipeline below the groundwater table, the uplift should be checked. In the subsequent calculation the safety factor for uplift is calculated based on an empty pipe.

4.1.1 Uplift Factors

Vertical nr.	Safety factor calculated [-]	Safety factor required [-]
1	999.00	1.00
2	999.00	1.00
3	999.00	1.00
4	7.73	1.00
5	4.28	1.00
6	2.38	1.00
7	6.79	1.00
8	8.29	1.00
9	50.03	1.00
10	999.00	1.00
11	999.00	1.00

Figure 6.27: *Report window, Uplift Check section*

Vertical nr.	[-]	Number of the calculation vertical.
Safety factor calculated	[-]	The calculated safety factor for uplift, see Equation 27.5 in section 27.1.
Safety factor required	[-]	The required safety factor for uplift as specified by the user in the *Factors* window (section 4.7.1.3).

Hydraulic Heave Check

In case of trenching in soil layers which cover an aquifer with high pore pressures, bursting of the bottom of the trench can be an installation risk which needs to be checked. Results are given per vertical in a table (Figure 6.28) and in graphs.

4.2 Hydraulic Heave Check

In case of high groundwater pressures in a water bearing soillayer below the trench the safety factor for heave of the trench bottom should be evaluated. Subsequently, the safety factors for heave are based on groundwater pressures at the top of layer:1 (Silty Sand) are calculated

4.2.1 Hydraulic heave of the trench bottom

Vertical nr.	Safety factor calculated [-]	Safety factor required [-]
1	0.73	1.00
2	0.73	1.00
3	0.60	1.00
4	0.55	1.00
5	0.51	1.00
6	0.51	1.00
7	0.53	1.00
8	0.55	1.00
9	0.58	1.00
10	0.73	1.00
11	0.73	1.00

Figure 6.28: *Report window, Hydraulic Heave Check section*

Vertical nr.	[-]	Number of the calculation vertical.
Safety factor calculated	[-]	The calculated safety factor for hydraulic heave, see Equation 27.7 in section 27.2.

Safety factor required	[-]	The required safety factor for hydraulic heave as defined by the user in the *Factors* window (section 4.7.1.3).

6.2.8 Report – Face Support Pressures and Thrust Forces (Micro tunneling)

Results are given per vertical in a table (Figure 6.29) and in graphs.

4.1 Face Support Pressure and Thrust Forces

4.1.1 Results table

The maximum allowable face support pressure and the minimum required face support pressure are calculated for the current soil conditions. The maximum allowable face support pressure should not be exceeded in order to prevent a frac-out. The minimum required face support pressure should not fall below the critical value in order to prevent surface subsidence. The neutral pressure is the pressure which yields minimal soil deformations during drilling.

Vertical nr.	Face Support Pressure			Thrust Forces	
	Pmax [kN/m²]	Pmin [kN/m²]	Pneutral [kN/m²]	Lubricated [kN]	Normal [kN]
1	191	68	135	435	530
2	191	68	135	1001	1284
3	191	68	135	1566	2038
4	191	68	135	2132	2792
5	191	68	135	2697	3546
6	191	68	135	3263	4300
7	191	68	135	3828	5054
8	191	68	135	4394	5808
9	191	68	135	4959	6562
10	191	68	135	5525	7316
11	191	68	135	6090	8069
12	191	68	135	6656	8823
13	191	68	135	7221	9577
14	191	68	135	7787	10331

Figure 6.29: *Report window, Operation Parameters section for Micro tunneling*

The following is an explanation of the column headings:

Vertical nr.	[-]	Number of the calculation vertical.
Pmax	[kN/m^2]	*Pmax* is the maximum allowable face support pressure which should not be exceeded in order to prevent the following possible failure mechanisms: ◇ Soil failure due to pushing a soil wedge in upward direction ◇ A blow out to the surface due to hydraulic fracturing ◇ Horizontal hydraulic fracturing at the transition of soil layers. Refer to Equation 26.7 in section 26.1.3.
Pmin	[kN/m^2]	*Pmin* is the minimum face support pressure required for stable conditions of the soil adjacent to the micro tunneling machine. Refer to Equation 26.2 for undrained layers and to Equation 26.4 for drained layers, in section 26.1.2.
Pneutral	[kN/m^2]	*Pneutral* is the target pressure, i.e. the total neutral horizontal soil pressure. Refer to Equation 26.1 in section 26.1.1.
Thrust Forces	[kN]	The thrust force is the force required to install a micro tunnel or pipeline in between the launch pit and the reception pit. Thrust forces are calculated in both cases: injection of lubricant (*Lubricated*) or not (*Normal*). Refer to Equation 26.8 in section 26.1.4.

6.2.9 Report – Thrust Forces (Direct Pipe)

6.2.9.1 Face support data

Results are given per vertical in a table (Figure 6.30).

3.1 Face Support Data

Vertical nr.	Face support			
	pressure [kN/m²]	Force [kN]	Additional [kN]	Total [kN]
1	0.00	85	100.00	184.72
2	12.65	101	100.00	201.38
3	25.30	118	100.00	218.04
4	37.95	135	100.00	234.70
5	57.31	160	100.00	260.20
6	77.64	187	100.00	286.99
7	96.88	212	100.00	312.32
8	115.02	236	100.00	336.22
9	132.07	259	100.00	358.67
10	148.03	280	100.00	379.69

Figure 6.30: *Report window, Face support data section for Direct Pipe*

Vertical nr.	[-]	Number of the calculation vertical.
Pressure	[kN/m^2]	xxx
Force	[kN]	The front force at the cutting head
Additional	[kN]	xxx
Total	[kN]	xxx

6.2.9.2 Forces

The results of the thrust forces are also given per vertical in a table.

Vertical nr.	[-]	Number of the calculation vertical.
Length in borehole	[m]	The length of the pipeline in the borehole.
Roll Force	[kN]	The friction force of the pipeline behind the thruster on the rollers. Refer to section 28.1.1 for more information.
Friction	[kN]	The friction between the pipeline and the lubricant/drilling fluid and between the pipeline and the borehole wall. Refer to section 28.1.2 and section 28.1.3 for more information.
Buckling Force	[kN]	The contact force of the pipeline against the borehole wall due to buckling. Refer to section 28.2.8 for more information.
Thrust Force no S.F.	[kN]	The thrust force ??
Thrust Force	[kN]	The total thrust force needed to push the pipeline into the borehole Refer to section 28.2 for more information.

6.3 Drilling Fluid Pressures Plots

Only available if the *Horizontal directional drilling* model in the *Model* window (section 4.1) is selected. In the *Results* menu, choose the *Drilling Fluid Pressures Plots* option to display the following plots for the three boring stages (pilot, pre-ream and pullback):

Maximum allowable drilling fluid pressure (plastic zone related to deformation bore hole)
Refer to Equation 24.28 in section 24.2.2 for drained layers and to Equation 24.22 in section 24.2.1 for undrained layers. For drained layers, the determination of the maximum allowable radius of the plastic zone $R_{\text{p;max}}$ is related to the deformation of the bore hole:

$$R_{\text{p;max}} = \sqrt{\frac{R_{\text{b}}^2}{Q} \times 2\varepsilon_{\text{g;max}}}$$

Maximum allowable drilling fluid pressure (plastic zone related to soil cover)
Refer to Equation 24.28 in section 24.2.2 for drained layers and to Equation 24.22 in section 24.2.1 for undrained layers. For drained layers, the determination of the maximum allowable radius of the plastic zone is related to the soil cover:

$$R_{\text{p;max}} = 0.5\ H$$

Minimum drilling fluid pressure assuming that the pilot is drilled from the left side to the right side
Refer to section 24.1 for background information.

Minimum drilling fluid pressure assuming that the pilot is drilled from the right side to the left side
Refer to section 24.1 for background information.

To select the stage, click on one of the three tabs of the *Drilling Fluid Pressures Plots* window (Figure 6.31): *Pilot*, *Prereaming* or *Reaming and pullback operation*.

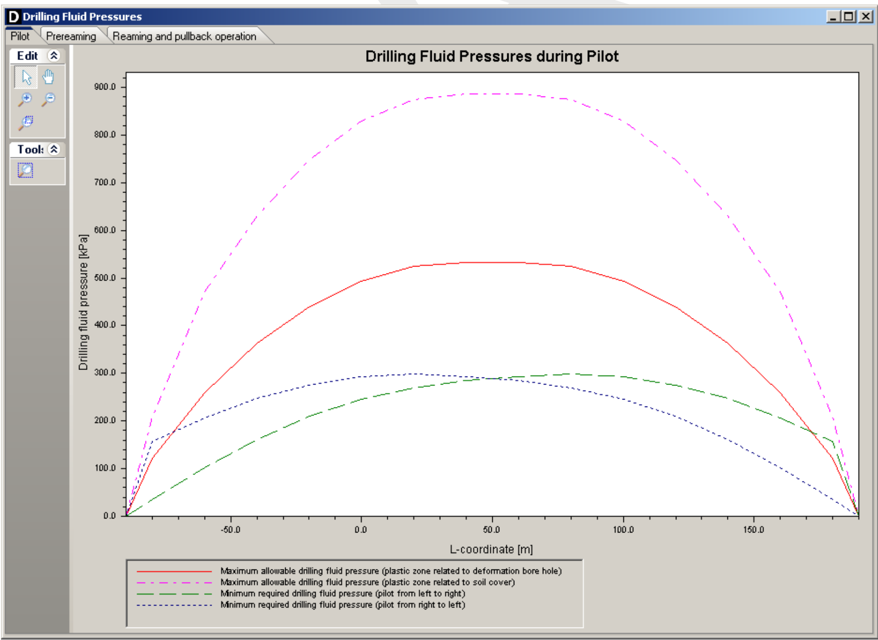


Figure 6.31: *Drilling Fluid Pressures Plots window*

Use the *Pan* and *Zoom* buttons to select the part to be viewed in detail.

6.4 Operation Parameter Plots

In the *Results* menu, choose the *Operation Parameter Plots* option. The content of the *Operation Parameter Plots* window depends on the selected model:

◇ Refer to section 6.4.1 for Micro tunneling;
◇ Refer to section 6.4.2 for Construction in trench.
◇ Refer to section 6.4.3 for Direct Pipe

6.4.1 Operation Parameter Plots for Micro Tunneling

For *Micro tunneling* model, the *Operation Parameter Plots* window displays three different plots by clicking on one of the three tabs:

◇ the face support pressures at the micro tunneling machine (Figure 6.32);
◇ the thrust pressures along the micro tunnel or pipe segments (Figure 6.33);
◇ the uplift safety factor along the micro tunneling (Figure 6.34).

Use the *Pan* and *Zoom* buttons to select the part to be viewed in detail.

For background information, refer to chapter 26.

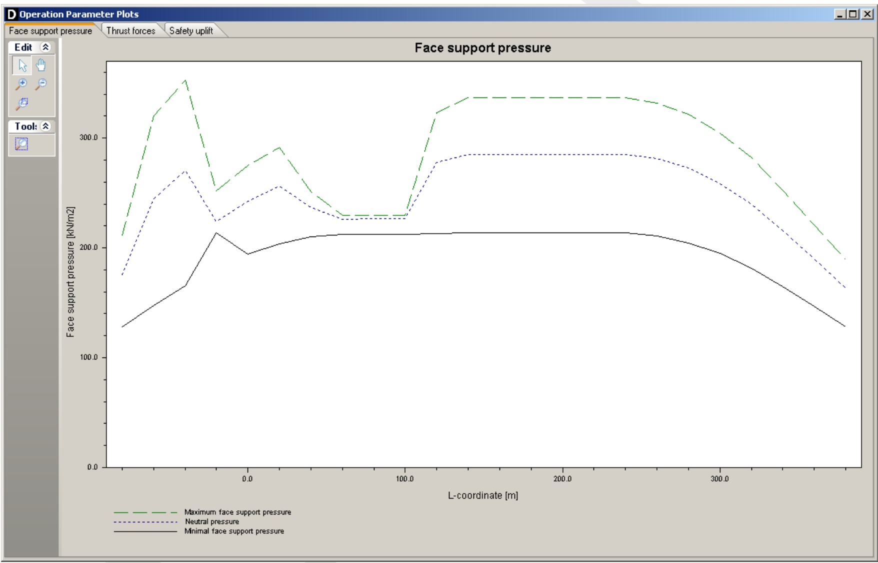


Figure 6.32: *Operation Parameter Plots window, Face support pressures tab*

Maximum face support pressure	The maximum allowable face support pressure which should not be exceeded in order to prevent the following possible failure mechanisms: ◇ Soil failure due to pushing a soil wedge in upward direction ◇ A blow out to the surface due to hydraulic fracturing ◇ Horizontal hydraulic fracturing at the transition of soil layers. For background information, refer to section 26.1.3.
Neutral pressure	The neutral pressure is the pressure with the lowest soil deformation, i.e. the total neutral horizontal soil pressure. For background information, refer to section 26.1.1.

Minimum face support pressure	The minimum face support pressure is the pressure required for stable conditions of the soil adjacent to the micro tunneling machine. For background information, refer to section 26.1.2.

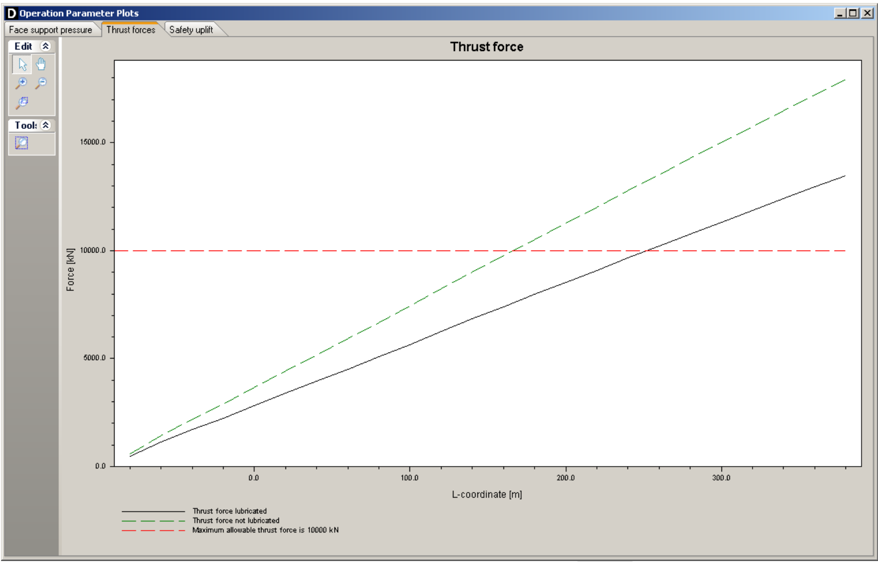


Figure 6.33: *Operation Parameter Plots window, Thrust pressures tab*

Thrust force lubricated	The thrust force lubricated is the force required to install a micro tunnel in between the launch pit and the reception pit in case of injection of lubricant. For background information, refer to section 26.1.4.
Thrust force not lubricated	The thrust force lubricated is the force required to install a micro tunnel in between the launch pit and the reception pit in case of no injection of lubricant. For background information, refer to section 26.1.4.
Maximum allowable thrust force	The maximum allowable thrust force is usually given by the manufacturer of the pipe and specified in the *Engineering Data* window (section 4.6.3).

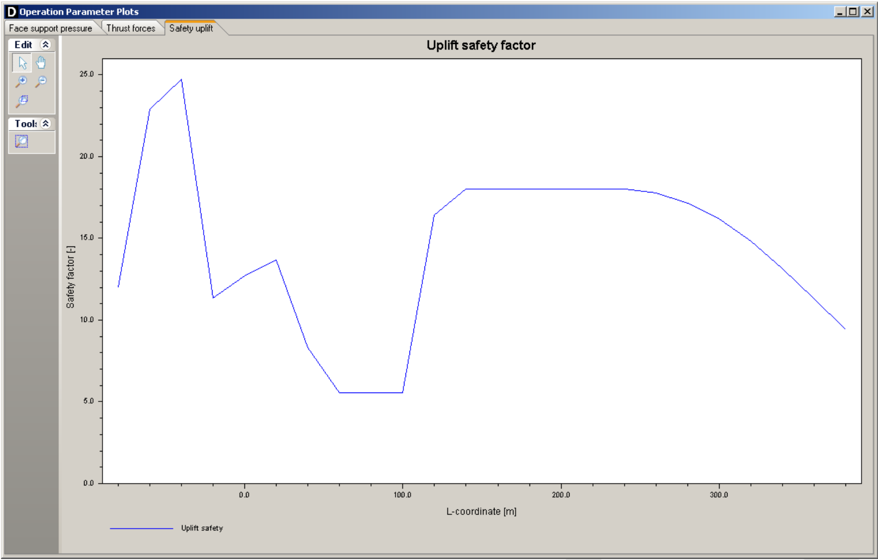


Figure 6.34: *Operation Parameter Plots window, Safety uplift tab*

6.4.2 Operation Parameter Plots for Construction in trench

For *Construction in trench* model, the *Operation Parameter Plots* window displays two different plots by clicking on one of the two tabs:

◇ the safety factor for uplift along the bottom of the trench (Figure 6.35);
◇ the safety factor for hydraulic heave along the bottom of the trench (Figure 6.39);

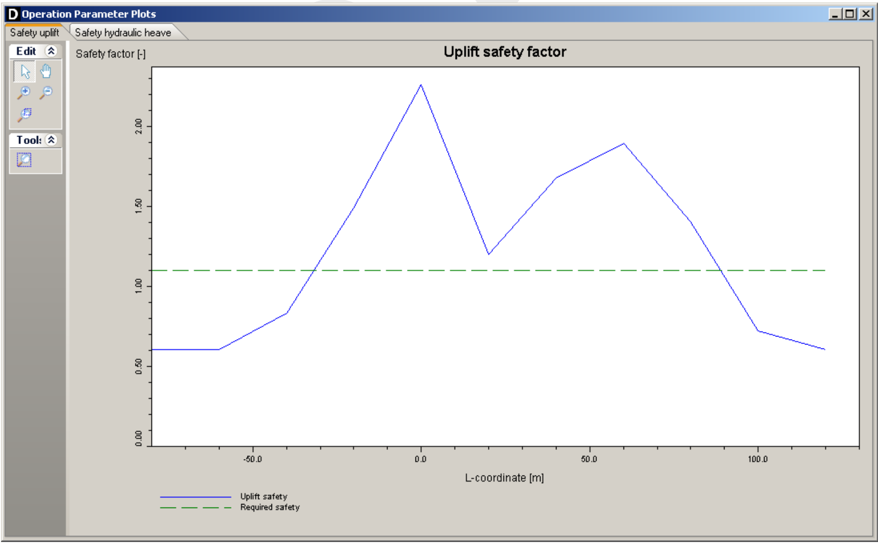


Figure 6.35: *Operation Parameter Plots window, Safety uplift tab*

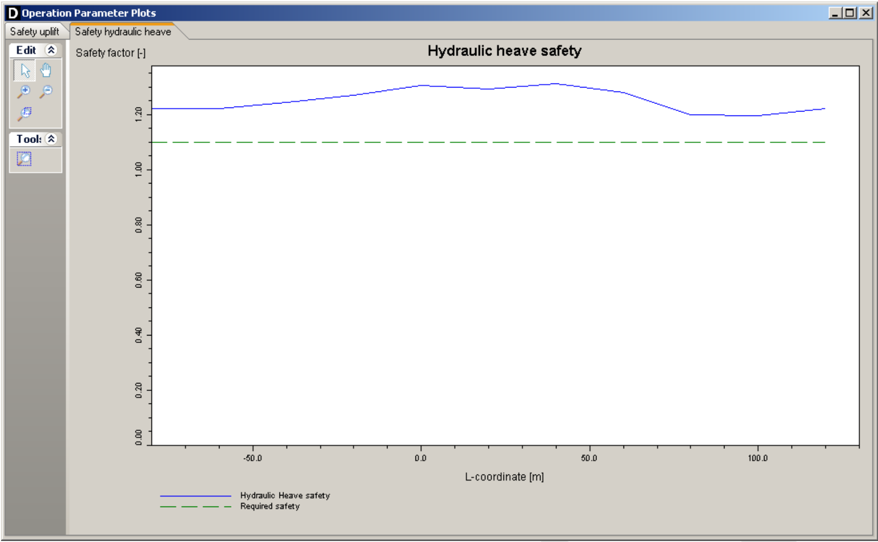


Figure 6.36: *Operation Parameter Plots window, Safety hydraulic heave tab*

6.4.3 Operation Parameter Plots for Direct Pipe

For the *Direct Pipe* model, the *Operation Parameter Plots* window displays two different plots by clicking on one of the two tabs:

- ◇ the face support pressure (Figure 6.37);
- ◇ the thrust forces (Figure 6.38);

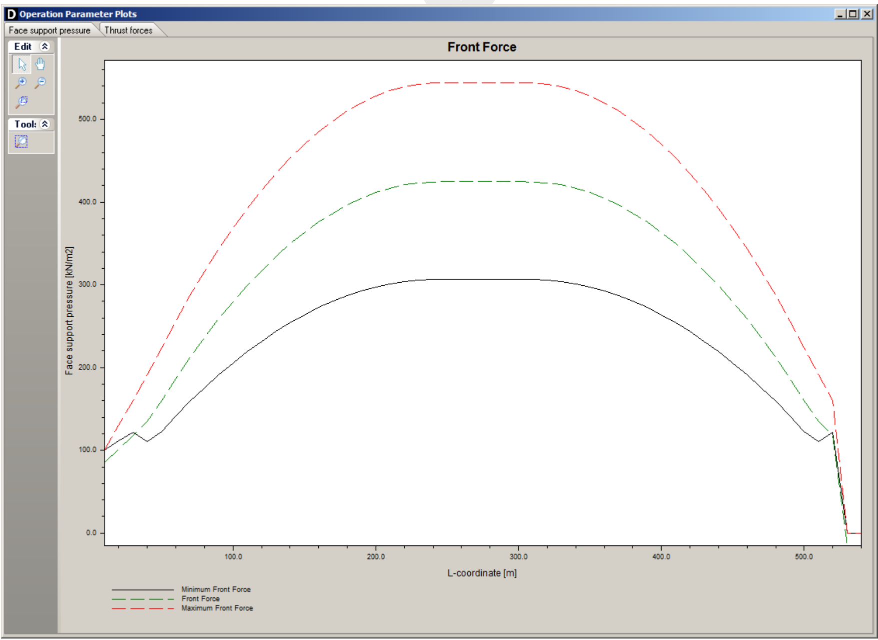


Figure 6.37: *Operation Parameter Plots window, Face support pressure tab*

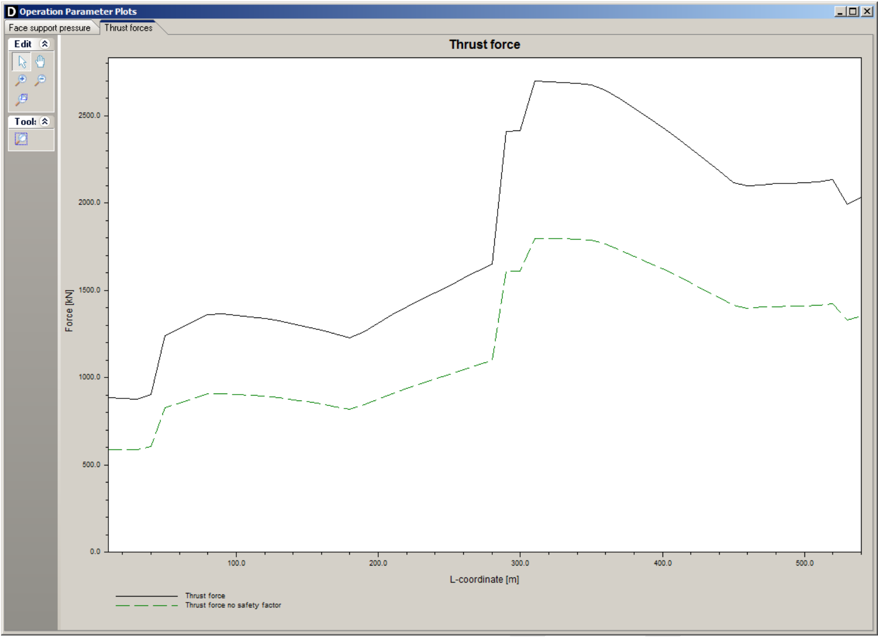


Figure 6.38: *Operation Parameter Plots window, Thrust forces tab*

6.5 Stresses in Geometry

In the *Results* menu, choose the *Stresses in Geometry* option to display the vertical stress per vertical drawn in the geometry. The blue part represents the water pressure and the dark green part represents the additional effective stress. Use the *Pan* and *Zoom* buttons to select the part to be viewed in detail.

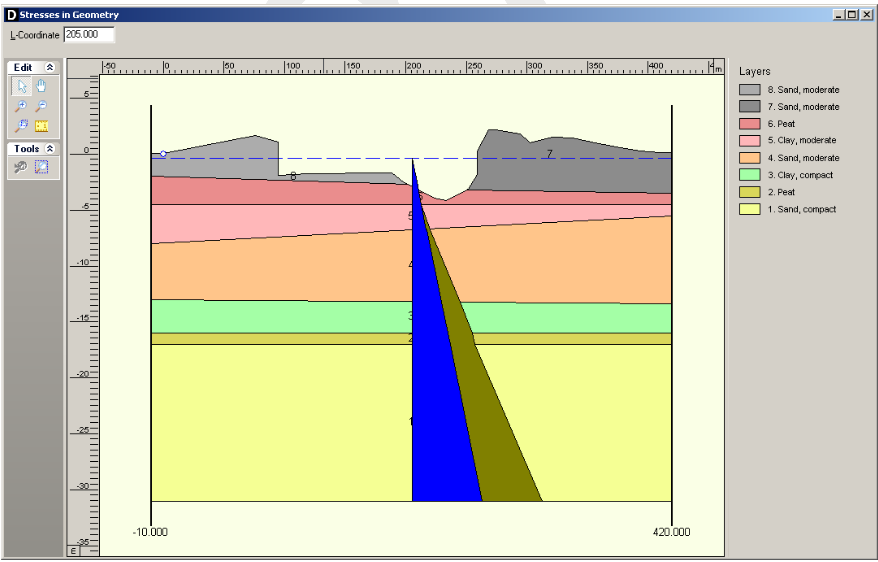


Figure 6.39: *Stresses in Geometry window*

6.6 Subsidence Profiles

Only available if the *Micro tunneling* model in the *Model* window (section 4.1) is selected. In the *Results* menu, choose the *Subsidence Profiles* option to display the calculation results for the subsidence trough as apparent at surface. Subsidence is related to the volume loss due to the tunnel excavation, e.g. the excess soil removed by the Micro Tunneling Boring Machine (MTBM). The subsidence mechanism is described in detail in section 26.3.

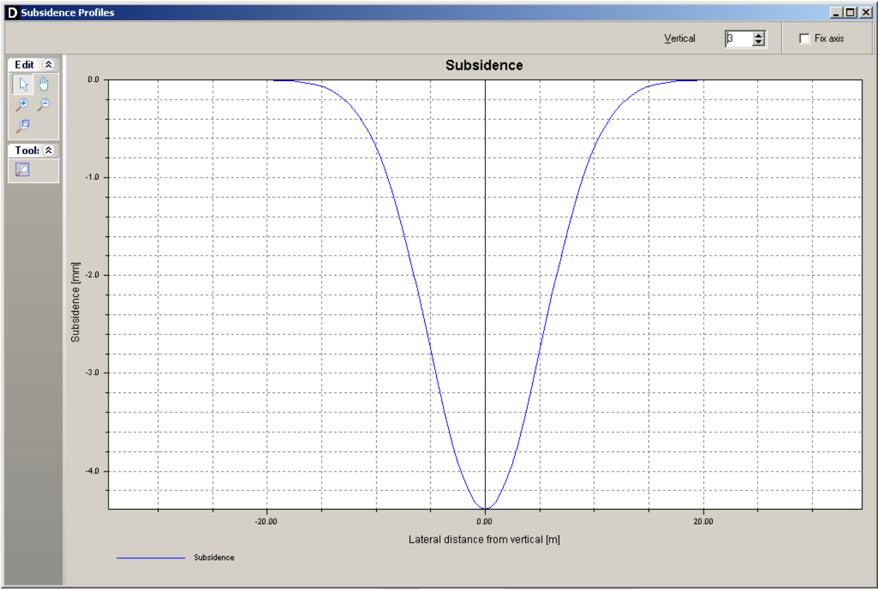


Figure 6.40: *Subsidence Profiles window*

Vertical	Type the vertical number that must be displayed or click the arrow-up and arrow-down keys to scroll through the available verticals.
Fix axis	Enable this check-box to fix the range of the vertical axis of the graph of subsidence whatever the selected time step.

Use the *Pan* and *Zoom* buttons to select the part to be viewed in detail.

7 Graphical Geometry Input

This chapter explains how to define the soil layers in a two-dimensional cross section by drawing, using the shared D-Series options for geometry modeling.

◇ section 7.1 introduces the basic geometrical elements that can be used.
◇ section 7.2 lists the restrictions and assumptions that the program imposes during geometry creation.
◇ section 7.3 gives an overview of the functionality of the *View Input* window.
◇ section 7.4 describes the creation and section 7.5 describes the manipulation of general graphical geometry using the *View Input* window.

Besides graphical input, the geometry can also be imported or tabular forms can be used (see section 4.3.2). See the MGeoBase manual for a description of special features to create cross-section geometry semi-automatically from CPT and/or boring records.

7.1 Geometrical objects

Geometry can be built step-by-step through the repetitive use of sketching, geometry creation and geometry manipulation. Each step can be started by using line-shaped construction elements (section 7.1.2) to add line drawings. After converting these drawings to valid geometry parts, the specific geometry elements created can be manipulated (section 7.1.1).

7.1.1 Geometry elements

Geometry can be composed from the following geometry elements:

Points	A point is a basic geometry element defined by its co-ordinates. As stated earlier, the geometry is restricted to two dimensions, allowing to define X and Z co-ordinates only.
Boundary lines	A boundary line is a straight line piece between two points and is part of a boundary.
Boundaries	A boundary is a collection of connected boundary lines that forms the continuous boundary between layers.
PL-lines	A piezometric level line is a collection of connected straight line pieces defining a continuous piezometric level.
Phreatic line	This is a PL-line that acts as phreatic line. The phreatic line (or ground-water level) is used to mark the border between saturated and unsaturated soil.
Layers	A layer is the actual soil layer. Its geometrical shape is defined by its boundaries, and its soil type is defined by its material.
Materials	A material defines the actual soil material (or soil type). It contains the parameters belonging to the soil type, such as its unsaturated weight and its saturated weight. A material can be connected to a layer in order to define the soil type of the layer.
Limits	A limit is a vertical boundary defining the 'end' at either the left or right side of the geometry. It is defined by an X co-ordinate only. Note that this is the only type of element that cannot be deleted.

Adding, moving and deleting the above-mentioned elements are subject to the conditions for a valid geometry (see section 7.2). For example, while dragging selected geometry elements, the program can perform constant checks on the geometry validity (section 7.4.4). Invalid parts will be shown as construction elements (thick blue lines).

7.1.2 Construction elements

Besides the D-Series geometry elements (section 7.1.1), special construction elements can also be used for sketching the geometry graphically. These elements are not a direct part of the geometry and the restrictions on editing (adding, moving, and deleting); these elements are therefore far less rigid. The only restriction that remains is that these elements cannot be moved and/or defined beyond the limits of the geometry.

Lines	A line Construction consists of a starting point and end point, both defined by a left-hand mouse click in the graphic input screen.
Poly-lines	A poly-line Construction consists of a series of connected lines, all defined by a left-hand mouse click in the graphic input screen.

Construction elements will be displayed as solid blue lines. Valid constructions elements are converted to geometry elements as soon as the geometry is (re-) generated. For more information on adding lines and poly-lines, see section 7.4.

7.2 Assumptions and restrictions

During geometrical modeling, the program uses the following assumptions.

- Boundary number 0 is reserved for the base.
- A soil layer number is equal to the boundary number at the top of the layer.
- The boundary with the highest number defines the soil top surface.
- A material (soil type) must be defined for each layer – except for layer 0 (base). Different layers can use the same material.
- All the boundaries must start and end at the same horizontal co-ordinates.
- Boundaries should not intersect, but they may coincide over a certain length.
- All horizontal co-ordinates on a boundary must be ascending – that is, the equation $X[i+1] \geq X[i]$ must be valid for each following pair of X co-ordinates (vertical parts are allowed).
- PL-lines may intersect and may coincide with each other over a certain length.
- PL lines and layer boundaries may intersect.
- All PL-lines must start and end at the same horizontal co-ordinate.
- All X co-ordinates on a PL-line must be strictly ascending – that is, the equation $X[i+1] > X[i]$ must be valid for each following pair of X co-ordinates (no vertical parts allowed).

One way for inputting geometry data is through the *Geometry* menu, as explained in the *Reference* section (section 4.3). This section describes an other way to create and manipulate geometry graphically using the tool buttons of the *View Input* window.

7.3 View Input Window

7.3.1 General

To use the *View Input* option, click the *Geometry* tab to activate it in the regular *View Input* window or use the menu to select it.

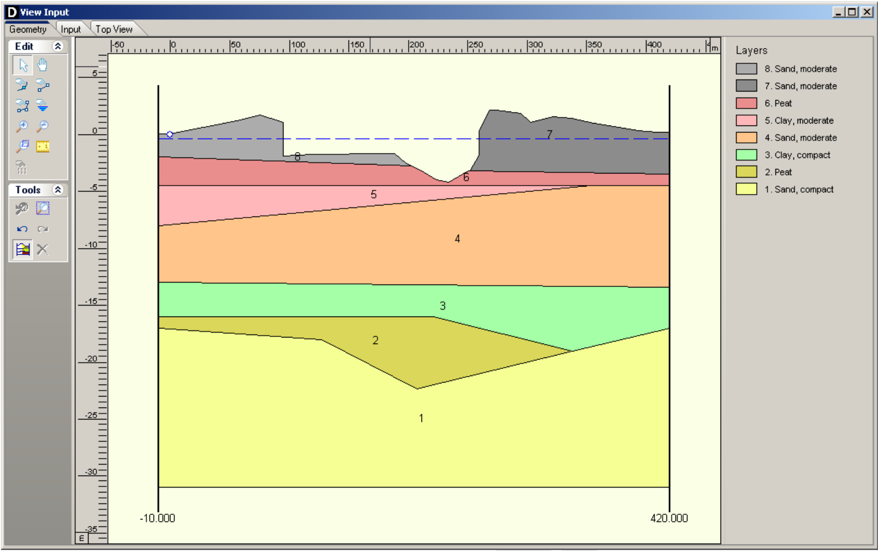


Figure 7.1: *View Input window, Geometry tab*

When the *Geometry* tab in the *View Input* window is selected, it displays a graphical representation of only the geometrical data. On the left of the window, the *Edit* and *Tools* buttons are displayed (section 7.3.2). On the right, the legend belonging to the geometry is displayed (section 7.3.3). At the bottom of the window, the title panel and the info bar are displayed. The title panel displays the project titles defined using the *Properties* option in the *Project* menu. The info bar provides information (from left to right) about the current cursor position, the current mode and the object currently selected. The legend, title panel and info bar are optional and can be controlled using the *Properties* option in the *Project* menu.

It is possible to use three different modes when working in the *Geometry* tab of the *View Input* window:

Select	The *Select* mode is the default mode and enables the user to select existing elements in the window.
Add	The *Add* mode allows the addition of elements using one of the *Add* buttons. By selecting one of these buttons, one switches to the *Add* mode. As long as this mode is active, the user can add the type of element which is selected.
Zoom	The *Zoom* mode allows the user to view the input geometry in different sizes. By selecting one of the *Zoom* buttons or the *Pan* button, one activates the *Zoom* mode. While in this mode, the user can repeat the zoom or pan actions without re-selecting the buttons.

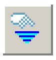
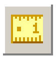
It is possible to change modes in the following ways. When in *Add* or *Zoom* mode, it is possible to return to the *Select* mode by clicking the right-hand mouse button, or by pressing the *Escape* key, or by clicking the *Select mode* button. To activate the *Add* mode, select one of the *Add* buttons. To activate the *Zoom* mode, select one of the *Zoom* buttons or the *Pan* button.

Note: The current mode is displayed on the info bar at the bottom of the *View Input* window.

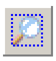
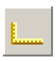
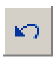
7.3.2 Buttons

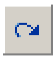
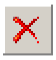
Edit panel:

	*Select* and *Edit* mode In this mode, the left-hand mouse button can be used to graphically select a previously defined grid, load, geotextile or forbidden line. Items can then be deleted or modified by dragging or resizing, or by clicking the right-hand mouse button and choosing an option from the menu displayed. Pressing the *Escape* key will return the user to this *Select* and *Edit* mode.
	*Pan* Click this button to change the visible part of the drawing by clicking and dragging the mouse.
	*Add point(s) to boundary / PL-line* Click this button to add points to all types of lines (lines, poly-lines, boundary lines, PL-lines). By adding a point to a line, the existing line is split into two new lines. This provides more freedom when modifying the geometry.
	*Add single lines(s)* Click this button to add single lines. When this button is selected, the first left-hand mouse click will add the info bar of the new line and a “rubber band” is displayed when the mouse is moved. The second left-hand mouse click defines the end point (and thus the final position) of the line. It is now possible to either go on clicking start and end points to define lines, or stop adding lines by selecting one of the other tool buttons, or by clicking the right-hand mouse button, or by pressing the *Escape* key.
	*Add polyline(s)* Click this button to add poly-lines. When this button is selected, the first left-hand mouse click adds the starting point of the new line and a “rubber band” is displayed when the mouse is moved. A second left-hand mouse click defines the end point (and thus the final position) of the first line in the poly-line and activates the “rubber band” for the second line in the poly-line. Every subsequent left-hand mouse click again defines a new end point of the next line in the poly-line. It is possible to end a poly-line by selecting one of the other tool buttons, or by clicking the right-hand mouse button, or by pressing the *Escape* key. This also stops adding poly-lines altogether. A different way to end a poly-line is to double-click the left-hand mouse button. Then the poly-line is extended automatically with an ‘end line’. This end line runs horizontally from the position of the double-click to the limit of the geometry in the direction the last line of the poly-line was added. Therefore, if the last line added was defined left to right, the ‘end line’ will stop at the right limit. Note that by finishing adding a poly-line this way, it is possible to start adding the next poly-line straight away.

	*Add PL-line(s)* Click this button to add a piezometric level line (PL-line). Each PL-line must start at the left limit and end at the right limit. Furthermore, each consecutive point must have a strictly increasing X co-ordinate. Therefore, a PL-line must be defined from left to right, starting at the left limit and ending at the right limit. To enforce this, the program will always relocate the first point clicked (left-hand mouse button) to the left limit by moving it horizontally to this limit. If trying to define a point to the left of the previous point, the rubber band icon indicates that this is not possible. Subsequently clicking on the left side of the previous point, the new point will be added at the end of the rubber band icon instead of the position clicked. As with poly-lines, it is also possible to end a PL-line by double-clicking the left-hand mouse button. In this case, the automatically added 'end line' will always end at the right limit. To stop adding PL-lines, select one of the other tool buttons, or click the right-hand mouse button, or press the *Escape* key.
	*Zoom in* Click this button to enlarge the drawing, then click the part of the drawing which is to be at the center of the new image. Repeat if necessary.
	*Zoom out* Click this button, then click on the drawing to reduce the drawing size. Repeat if necessary.
	*Zoom rectangle* Click this button then click and drag a rectangle over the area to be enlarged. The selected area will be enlarged to fit the window. Repeat if necessary.
	*Measure the distance between two points* Click this button, then click the first point on the View Input window and place the cross on the second point. The distance between the two points can be read at the bottom of the View Input window. To turn this option off, click the escape key.
	*Add calculation vertical* Click this button to graphically define the position of a vertical.

Tools panel:

	*Undo zoom* Click this button to undo the zoom. If necessary, click several times to retrace each consecutive zoom-in step that was made.
	*Zoom limits* Click this button to display the complete drawing.
	*Same scale for X and Y axis* Click this button to use the same scale for the horizontal and vertical directions.
	*Automatic regeneration of geometry on/off* When selected, the program will automatically try to generate a new valid geometry whenever geometry modifications require this. During generation, (poly)lines (solid blue) are converted to boundaries (solid black), with interjacent layers. New layers receive a default material type. Existing layers keep the materials that were assigned to them. Invalid geometry parts are converted to construction elements. Automatic regeneration may slow down progress during input of complex geometry, because validity will be checked continuously.
	*Undo* Click this button to undo the last change(s) made to the geometry.

	*Redo* Click this button to redo the previous Undo action.
	*Delete* Click this button to delete a selected element. Note that this button is only available when an element is selected. See section 7.5.2 for more information on how using this button.

7.3.3 Legend

At the right side of the *View Input* window (Figure 7.2) the legend belonging to the geometry is shown. This legend is present only if the *Legend* check-box in the *View Input* tab of the *Project Properties* window is activated (see section 4.1.2).

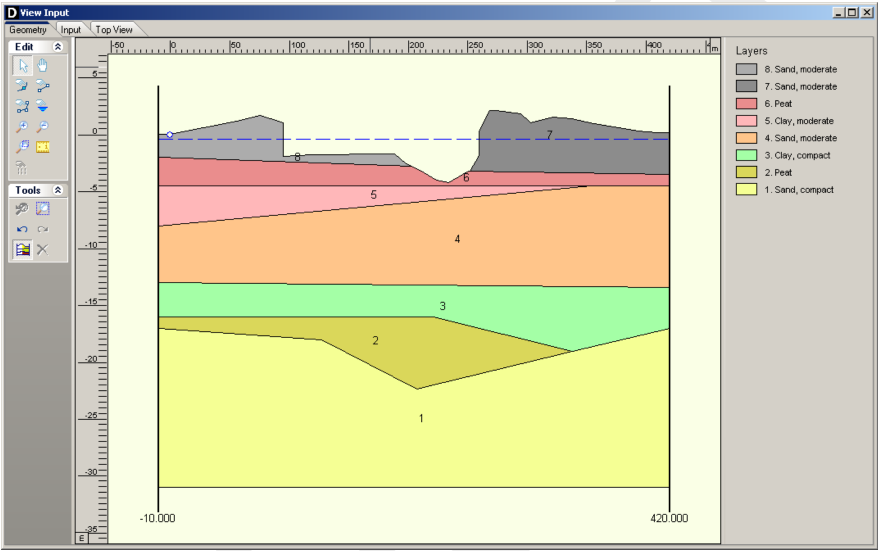


Figure 7.2: *View Input window, Geometry tab (legend displayed as Layer Numbers)*

In the *Geometry* tab of the *View Input* window, it is possible to change the type of legend. When a soil type box in the legend is right clicked, the menu from Figure 7.3 is displayed.

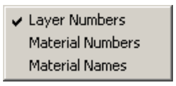


Figure 7.3: *Legend, Context menu*

With this menu, there are three ways to display the legend of the layers:

- ◇ As *Layer Numbers*: the legend displays one box for each layer. Each layer (and therefore each box) is displayed in a different standard color. Next to each box, the layer number and the material name are displayed, corresponding to the color and number of the layer in the adjacent *Geometry* window (see Figure 7.2).
- ◇ As *Material Numbers*: the legend displays one box for each material. Each material (and therefore each box) is displayed in a different color which can be changed by the user (see below). Next to each box, the material number and name are displayed, corresponding to the color and number of the material in the adjacent *Geometry* window (see Figure 7.4).

◇ As *Material Names*: the legend displays one box for each material. Each material (and therefore each box) is displayed in a different color which can be changed by the user (see below). Next to each box, only the material name is displayed, corresponding to the color and name of the material in the adjacent *Geometry* window (see Figure 7.5).

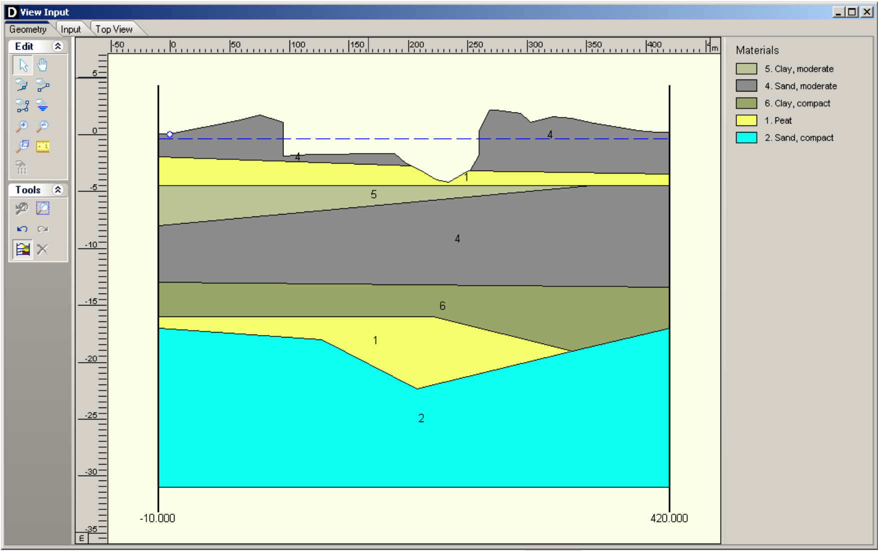


Figure 7.4: *View Input window, Geometry tab (legend displayed as Material Numbers)*

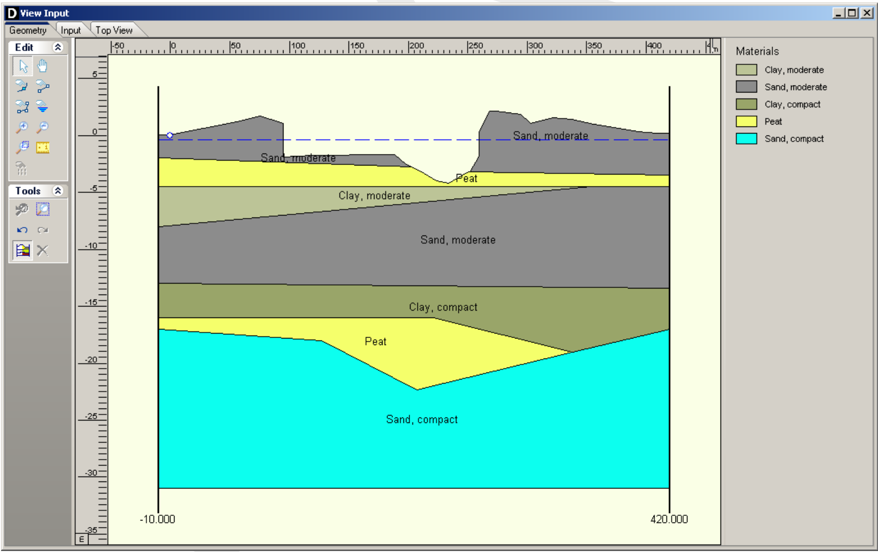


Figure 7.5: *View Input window, Geometry tab (legend displayed as Material Names)*

Unlike the standard colors used to display layers with their layer colors, it is possible to define different colors used when displaying materials. To change the color assigned to a material, right click the material box. The menu from Figure 7.6 is displayed.

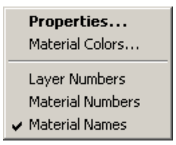


Figure 7.6: *Legend, Context menu (for legend displayed as Materials)*

When selecting *Material Colors* the *Color* window appears (Figure 7.7), in which the user can pick a color or even define customized colors himself (by clicking the *Define Custom Colors* button).

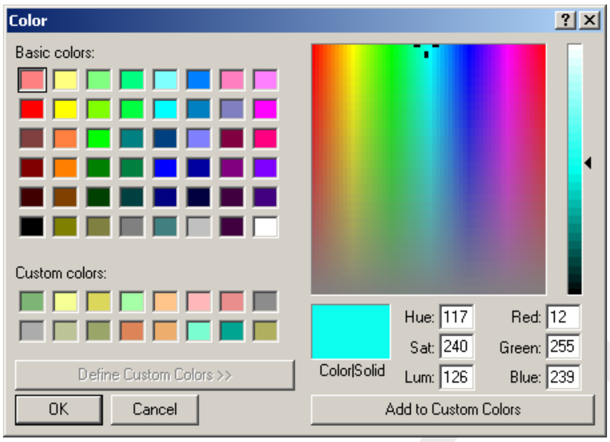


Figure 7.7: *Color window*

7.4 Geometry modeling

7.4.1 Create a new geometry

There are two ways to create a new geometry without the wizard:

- ◇ Open the *Geometry* menu and choose *New*.
- ◇ Open the *File* menu and choose *New*. In the *New File* window displayed, select *New Geometry* and click *OK* (see section 4.3.2).

In both cases, the *Geometry* tab of the *View Input* window is displayed (Figure 7.8) with the default limits of the geometry (from 0 to 100 m).

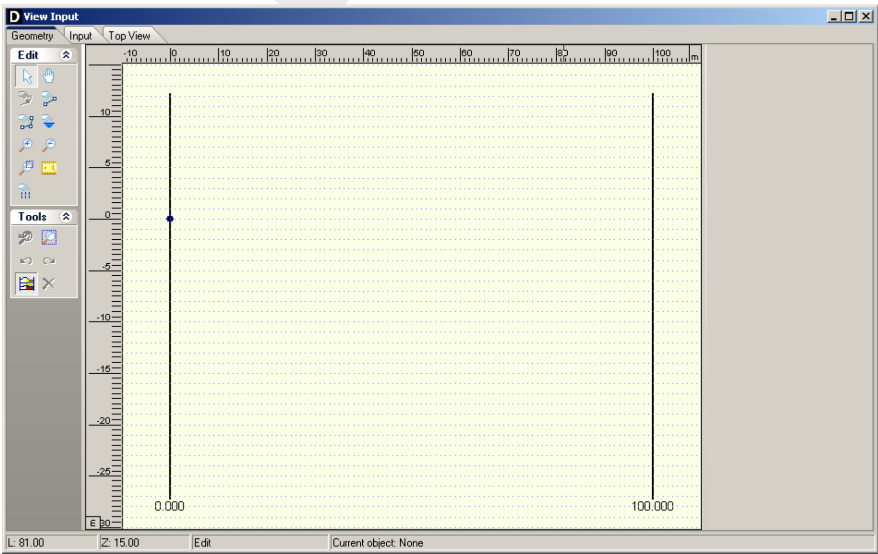


Figure 7.8: *View Input window, Geometry tab*

7.4.2 Set limits

The first thing to do when creating new geometry is to set the model limits. This is possible by selecting and then dragging the limits to their proper place one by one. It is also possible to select a limit and edit its value by clicking the right-hand mouse button after selecting the limit and then choosing the *Properties* option in the pop-up menu. The property window belonging to the selected limit is displayed (Figure 7.9), enabling to define the new X co-ordinate for this limit.

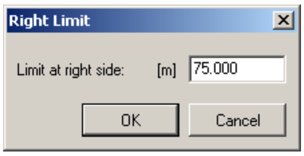


Figure 7.9: *Right Limit window*

7.4.3 Draw layout

It is possible to use the *Add single line(s)*, *Add polyline(s)* and *Add point(s) to boundary / PL-line* buttons to draw the layout of the geometry. See section 7.3.2 for more information's on how using those buttons.

Add single line(s)  **and Add polyline(s)** 

Each (poly)line is displayed as a solid blue line, and each point as a small black rectangle (Figure 7.10).

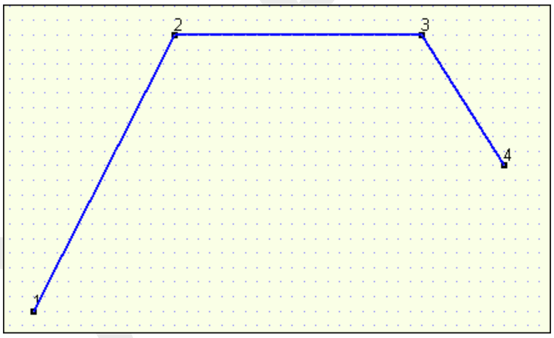


Figure 7.10: *Representation of a polyline*

The position of the different points of a (poly)line can be modified by dragging the points as explained in section 7.5.4 or by editing the (poly)line. This is done by clicking the right-hand mouse button after selecting the (poly)line and then choosing the *Properties* option in the pop-up menu.

The underlying grid helps the user to add and edit (poly)lines. Use the *Properties* option in the *Project* menu to adjust the grid distance and force the use of the grid by activating *Snap to grid*. When this option is activated, each point is automatically positioned at the nearest grid point.

The specified line pieces must form a continuous line along the full horizontal width of the model. This does not mean that each line piece has to be connected exactly to its predecessor and/or its successor. Intersecting line pieces are also allowed, as shown in the examples of Figure 7.11.

(1) (2) (3)

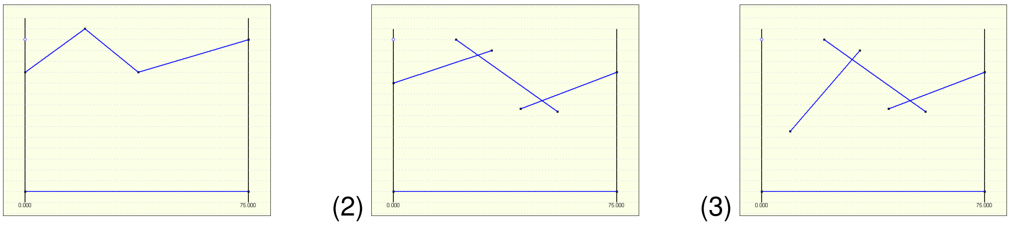


Figure 7.11: *Examples of configurations of (poly)lines*

- ◇ Configuration (1) is allowed. The different lines are connected and run from boundary to boundary
- ◇ Configuration (2) is also allowed. The different are connected. They are defined as being connected because they intersect. The line construction runs from boundary to boundary.
- ◇ Configuration (3) is illegal, as there is no connection with the left boundary.

Add point(s) to boundary / PL-line

Use this button to add extra points to lines (lines, polylines, boundary lines, PL-lines). By adding a point to a line, the existing line is split into two new lines. This provides more freedom when modifying the geometry.

Note: When the *Add point(s) to boundary/PL-line* button is clicked, each left-hand mouse click adds a new point to the nearest line until one of the other tool buttons is selected, or click the right-hand mouse button, or press the *Escape* key.

7.4.4 Generate layers

Use the *Automatic regeneration of geometry on/off* button to start or stop the automatic conversion of construction elements to actual boundaries and layers. Valid (poly)lines are converted to boundaries, which are displayed as black lines. Invalid lines remain blue.

Layers are generated between valid boundaries, and default soil types are assigned.

It is possible to modify the soil type assigned to a layer by first selecting the layer and then clicking the right-hand mouse button and choosing the *Layer Properties* option in the pop-up menu to display the *Layer* window (see Figure 7.19 in section 7.5.3). Once a material has been assigned to a layer, this material will continue to be associated to that layer in subsequent conversions of construction elements as long as the layer is not affected by those conversions.

The most common cause of invalid (poly)lines is that they are not part of a continuous polyline running from limit to limit. Sometimes, lines appear to start/end at a limit without actually being on a limit. Figure 7.12 gives an example: on the left geometry (1), the end of the line seems to coincide with the boundary. However, zooming in on the point (geometry (2) on the right) reveals that it is not connected to the boundary. Therefore the geometry is considered invalid.

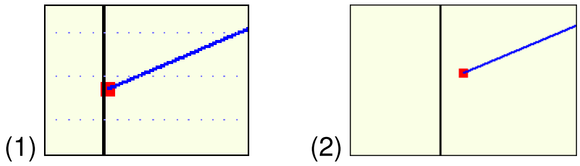


Figure 7.12: *Example of invalid point not connected to the left limit*

It is possible to correct this by dragging the point to the limit while the specific area is zoomed in or by selecting the point, clicking the right-hand mouse button, choosing the *Properties* option in the pop-up menu (section 7.5.3) and making the X co-ordinate of the point equal to the X co-ordinate of the limit.

7.4.5 Add piezometric level lines

It is possible to use the *Add PL-line(s) to add PL-lines*  button. When adding a PL-line, D-GEO PIPELINE imposes the limitation that the subsequent points of the PL-line have an increasing X co-ordinate. Furthermore the first point of a PL-line is to be set on the left boundary and the last point on the right boundary.

It is possible to change the position of the different points of a PL-line by dragging the points as explained in section 7.5.4 or by editing the PL-line. This is done by selecting the PL-line, clicking the right-hand mouse button and choosing the *Properties* option in the pop-up menu (section 7.5.3).

7.5 Graphical manipulation

7.5.1 Selection of elements

After selecting a geometry element it is possible to manipulate it. In order to be able select a geometry element, the select mode should be active. Then it is possible to select an element by clicking the left-hand mouse button. To select a layer, click on the layer number, material number or material name, depending on the option chosen in the *Properties* dialog in the *Project* menu. When successfully selected, the element will be displayed highlighted (for example, a point will be displayed as a large red box instead of a small black box).

The following remarks are relevant to selection accuracy and ambiguity.

Ambiguous selection

A selection of geometrical elements can be ambiguous. Figure 7.13 gives an example: a user may want to select a point, a boundary line, a boundary or a PL-line. As several elements are in close proximity to each other, D-GEO PIPELINE does not automatically select an element.

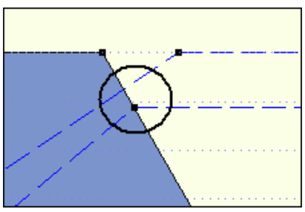


Figure 7.13: *Selection accuracy as area around cursor*

In this case D-GEO PIPELINE requires the user to assign the element that is to be selected by displaying a pop-up menu (Figure 7.14) with the available types of elements within the range of the selection click. It is possible to select the element from this menu.

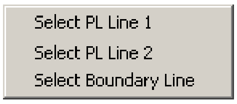


Figure 7.14: *Selection accuracy as area around cursor*

Clear selection

It is possible to clear a selection by clicking in an area without geometry elements in the direct area.

7.5.2 Deletion of elements

Click the *Delete* button  to delete a selected element. This button is only available when an element is selected.

When a point is selected and deleted, it and all lines connected to it are deleted as shown in Figure 7.15.

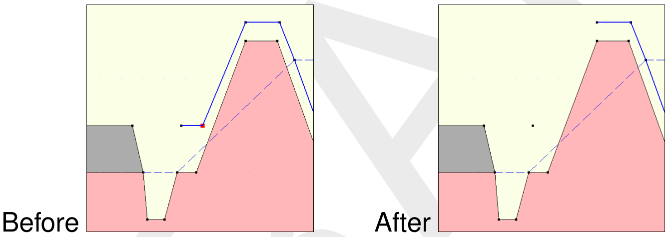


Figure 7.15: *Example of deletion of a point*

When a geometry point (a point used in a boundary or PL-line) is selected and deleted, the program deletes the point and its connected boundary lines as shown in Figure 7.16. It then inserts a new boundary that reconnects the remaining boundary lines to a new boundary.

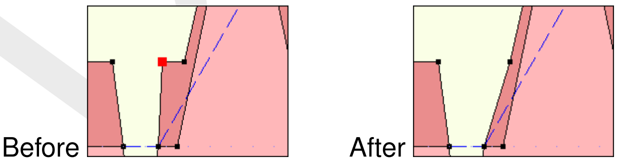


Figure 7.16: *Example of deletion of a geometry point*

Deletion of a geometry element (boundary, boundary line, geometry point, PL-line) can result in automatic regeneration of a new valid geometry, if the *Automatic regeneration* option is switched on.

When a line is selected and then deleted, the line and its connecting points are deleted as shown in Figure 7.17. In addition the layer just beneath that boundary is deleted. All other line parts that are not part of other boundaries will be converted to construction lines.

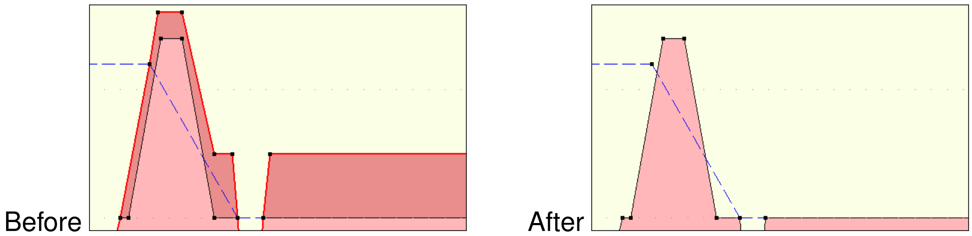


Figure 7.17: *Example of deletion of a line*

7.5.3 Using the right-hand mouse button

When using the mouse to make geometrical manipulations, the right mouse button enables full functionality in a pop-up menu, while the left button implies the default choice. The options available in the pop-up menu depend on the selected geometrical element and the active mode.

When the *Select* mode is active and the right-hand mouse button is clicked, the pop-up menu of Figure 7.18 is displayed.

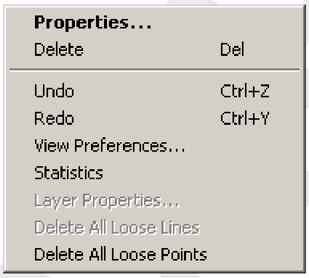


Figure 7.18: *Pop-up menu for right-hand mouse menu (Select mode)*

Properties...	When this option is clicked, the property editor for the selected object is displayed. This procedure is performed by first selecting an object by clicking on it with the left-hand mouse button. Then clicking the right-hand mouse button anywhere in the graphic window will display the pop-up menu. It is possible to use the property editor to quickly adapt the values (properties) of the selected object. Each type of element requires its own properties and therefore its own property editor as shown from Figure 7.20 to Figure 7.23 below.
Delete	This option deletes the element that has been selected (see the comments for the *Delete* button in section 7.5.2).
Undo	This option will undo the last change(s) made to the geometry.
Redo	This option will redo the previous *Undo* action.
View Preferences...	This option opens the *Properties* dialog in the *Project* menu as displayed in.
Statistics	It is possible to use this option to view a window displaying all the vital statistics of the input data. Note that in the window construction lines are called free lines.
Layer Properties...	This option is a special feature that edits the material properties of layers. It is possible to click anywhere in a layer and directly choose this option to edit its properties (Figure 7.19). Clicking outside the geometry layers will display the menu with the *Layer Properties* option disabled, as there is no layer for which properties can be displayed.

Delete All Loose Lines	This option will delete all loose lines. Loose lines are actually construction lines that are not part of the boundaries or PL-lines (therefore, all lines displayed as solid blue lines). With this option, it is possible to quickly erase all the "leftover bits" of loose lines that may remain after converting lines to a geometry.
Delete All Loose Points	This option will delete all loose points.

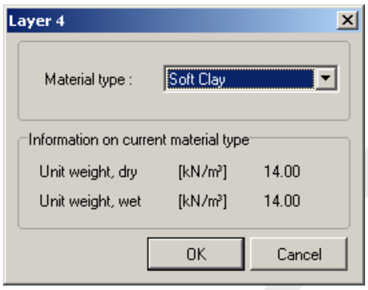


Figure 7.19: *Layer window (Property editor of a layer)*

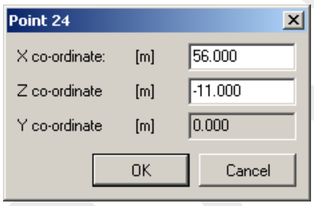


Figure 7.20: *Point window (Property editor of a point)*

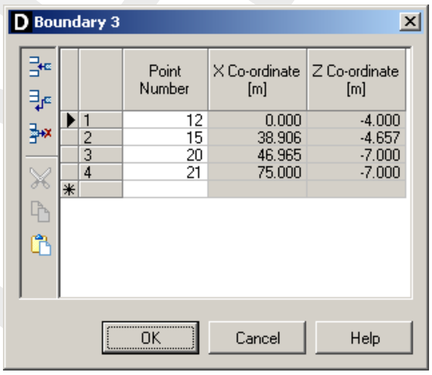


Figure 7.21: *Boundary window (Property editor of a polyline)*

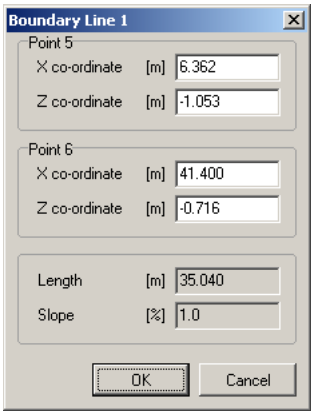


Figure 7.22: *Boundary window (Property editor of a line)*

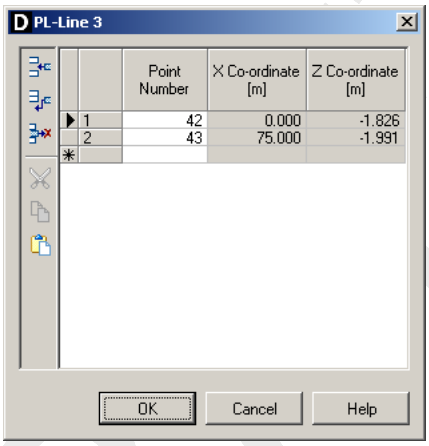


Figure 7.23: *PL-line window (Property editor of a PL-line)*

Note: In the *Boundary* and *PL-line* properties windows, only the point's number can be modified, not the X and Z co-ordinates.

7.5.4 Dragging elements

One way to modify elements is to drag them to other locations. To drag an element, first select it. Once the element has been selected, it is possible to drag it by pressing and holding down the left-hand mouse button while relocating the mouse cursor. Dragging of geometry elements can result in automatic regeneration of geometry, if this option is switched on (section 7.4.4) as shown in the example of Figure 7.24: when the selected point is moved upwards, a new geometry will be created. D-GEO PIPELINE creates new layers according to this new geometry.

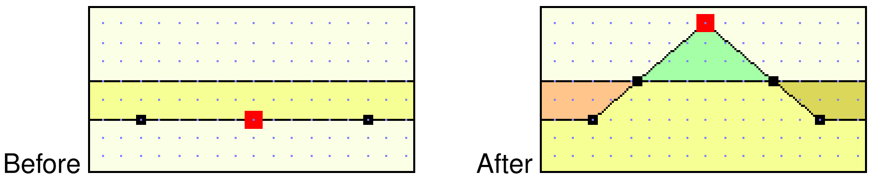


Figure 7.24: *Example of dragging of a point*

8 Tutorial 1: Calculation and assessment of the drilling fluid pressure

This first exercise considers installation of a steel pipeline by using the horizontal directional drilling technique. The exercise focuses on the calculation of the minimal required drilling fluid pressure which is necessary to perform a horizontal directional drilling and the maximum allowable drilling fluid pressure, which depends on the strength and deformability of the soil through which the drilling is carried out.

The objectives of this tutorial are:

- ◇ To learn how to start up a calculation in D-GEO PIPELINE;
- ◇ To calculate the minimum required drilling fluid pressure;
- ◇ To calculate the maximum allowable drilling fluid pressure;
- ◇ Assessment of the calculated drilling fluid pressures.

The following module is needed:

- ◇ D-GEO PIPELINE Standard module (HDD)

This tutorial is presented in the file Tutorial-1.dri.

8.1 Introduction to the case

The horizontal directional drilling technique is used to install a steel pipeline in a silty sand layer. The pipeline configuration is shown in Figure 8.1. The soil properties are provided in Table 8.1.

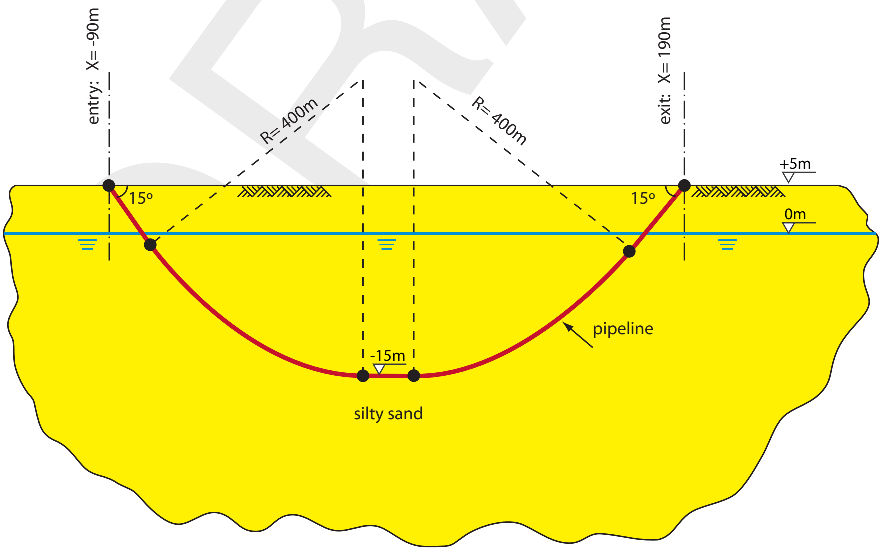


Figure 8.1: *Pipeline configuration for Tutorial 1*

Table 8.1: *Properties of the silty sand layer (Tutorial 1)*

Dry unit weight	[kN/m^3]	18
Wet unit weight	[kN/m^3]	20
Cohesion	[kN/m^2]	0
Angle of internal friction	[°]	30
Undrained strength top	[kN/m^2]	0
Undrained strength bottom	[kN/m^2]	0
E modulus top	[kN/m^2]	10000
E modulus bottom	[kN/m^2]	15000
Poisson's ratio	[-]	0.35

The pipeline material used in this tutorial is a steel 240 and its properties are given in Table 8.2.

Table 8.2: *Properties of steel material (Tutorial 1)*

Material quality		Steel 240
Negative wall thickness tolerance	[%]	0
Yield strength	[N/mm^2]	240
Partial material factor	[-]	1.1
Partial material factor test pressure	[-]	1
Young's modulus	[N/mm^2]	205800
Outer diameter	[mm]	323.9
Wall thickness	[mm]	7
Unit weight pipe material	[kN/m^3]	78.50
Design pressure	[Bar]	8
Test pressure	[Bar]	9
Temperature variation	[°C]	5

8.2 Project

8.2.1 Start

To create a new project, follow the steps described below:

1. Start D-GEO PIPELINE from the Windows task-bar (Start/Programs/Deltares Systems/ D-GEO PIPELINE).
2. Click *File* and choose *New* on the menu bar to start a new project.
3. In the *New File* window, select the option *New geometry* to start (Figure 8.2).

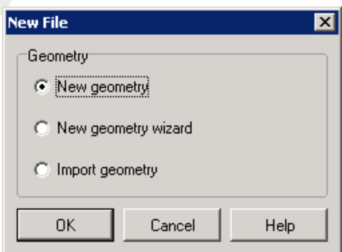


Figure 8.2: *New File window*

This will result in the empty geometry window shown in Figure 8.3.

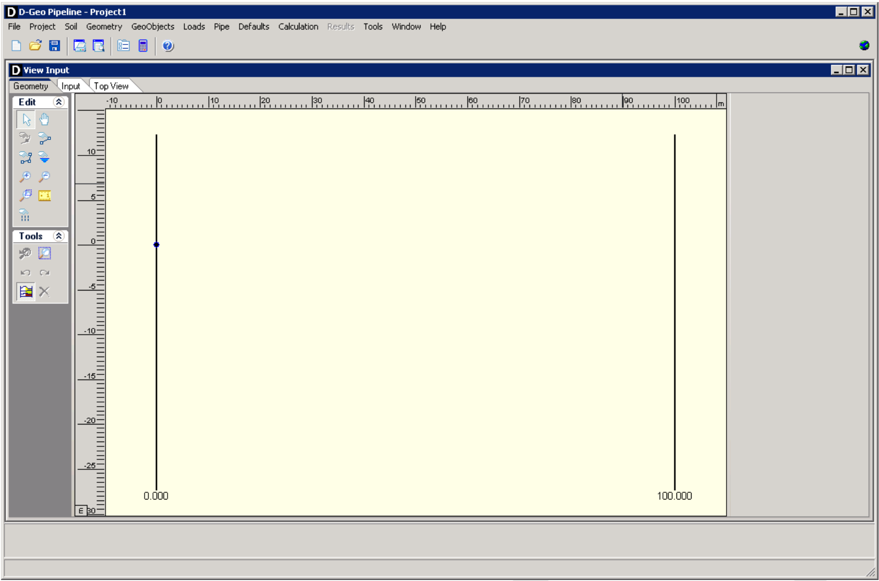


Figure 8.3: *View Input window*

4. Save the project by clicking *Save As* in the *File* menu and by entering <Tutorial-1> as project name.
5. Click *Save* to close this window.

8.2.2 Project Properties

To give the project a meaningful description, follow the steps described below:

6. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window (Figure 8.4).

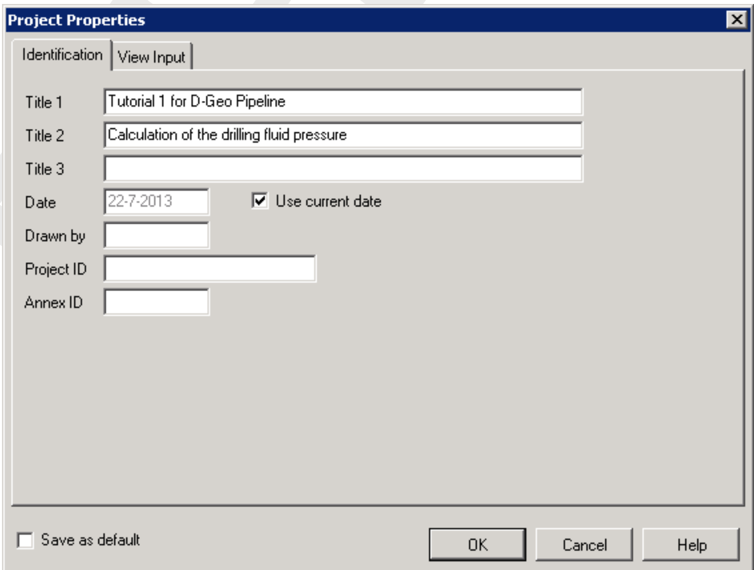


Figure 8.4: *Project Properties window, Identification tab*

7. Fill in <Tutorial 1 for D-GEO PIPELINE > and <Calculation of the drilling fluid pressure> for *Title 1* and *Title 2* respectively in the *Identification* tab.

In the other tab of the *Project Properties* window, some defaults values are modified in order to make the graphical geometry more understandable.

8. Select the *View Input* tab (Figure 8.5) to change the settings of the *View Input* window.

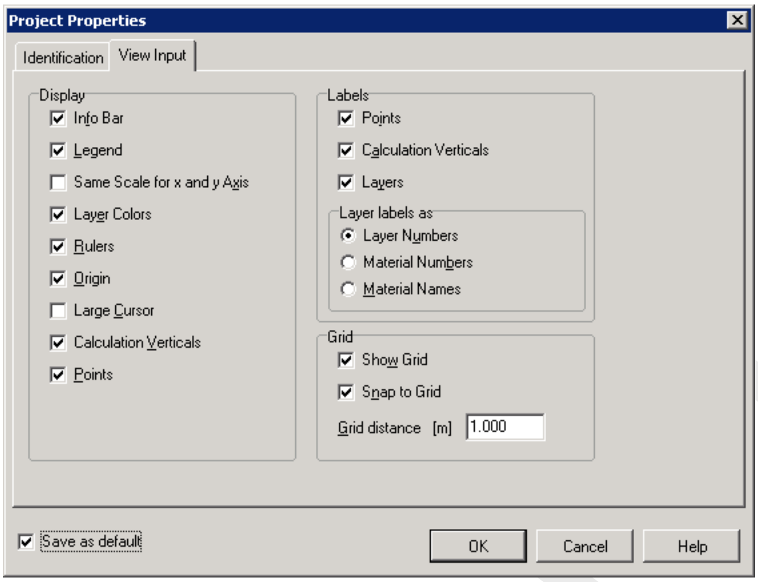


Figure 8.5: *Project Properties window, View input tab*

9. Mark the *Points* check-box of the *Labels* sub-window in order to display the point's number.
10. Mark the *Snap to grid* check-box in order to ensure that objects align to the grid automatically when they are moved or positioned.
11. Before closing the *Project Properties* window, mark the *Save as default* check-box to use the settings previously inputted every time D-GEO PIPELINE is started, which means for the other tutorials.
12. Click *OK* to confirm.

8.2.3 Model

The horizontal directional drilling technique is used in this first tutorial.

13. Select *Model* from the *Project* menu bar to open the *Model* window (Figure 8.6).
14. Check that the *Horizontal directional drilling* model is selected (default model).
15. Click *OK* to confirm.

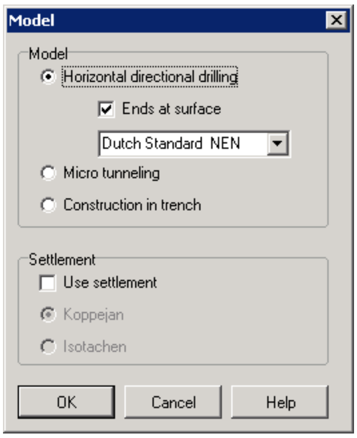


Figure 8.6: *Model window*

8.3 Geometry

Firstly, the geometry of Figure 8.1 needs to be put in D-GEO PIPELINE. In order to do this, the following actions should bee performed:

16. First enlarge the dimensions of the geometry window by selecting the left boundary by clicking the left mouse button, then click the right button and select *Properties*. This will result in the coordinate window for the left boundary as shown in Figure 8.7. Enter coordinate X of $<$-100 m$>$.

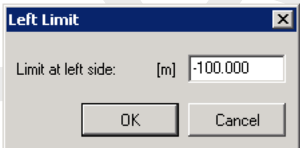


Figure 8.7: *Left Limit window*

17. Repeat the previous described actions for the right boundary and shift the boundary to coordinate X of $<$200 m$>$. The width in between the left and the right boundary is now 300 m.
18. Choose the drawing option *Zoom limits* from the *Tools* section so that the drawn geometry appears in the center of the screen.
19. Choose the drawing option from the edit-window *Add single line* to draw the surface line of the longitudinal cross section of the horizontal directional drilling and position the straight surface line at Z = 5 m. Use the right mouse button to finish the line.
20. Choose the drawing option *Add single line* to draw the lower boundary of the longitudinal cross section of the horizontal directional drilling and position the straight lower boundary line at Z = –40 m.
21. Choose the drawing option from the *Tools* section *Automatic regeneration of geometry* so that the geometry as shown in Figure 8.8 appears. If the *Automatic regeneration* option already is selected, click on the *Edit* icon to regenerate the geometry.
22. Choose the drawing option from the edit-window *Add pl-line(s)* and position the level of the groundwater at coordinate Z = 0 m. The blue dashed line represents the groundwater line (PL line).

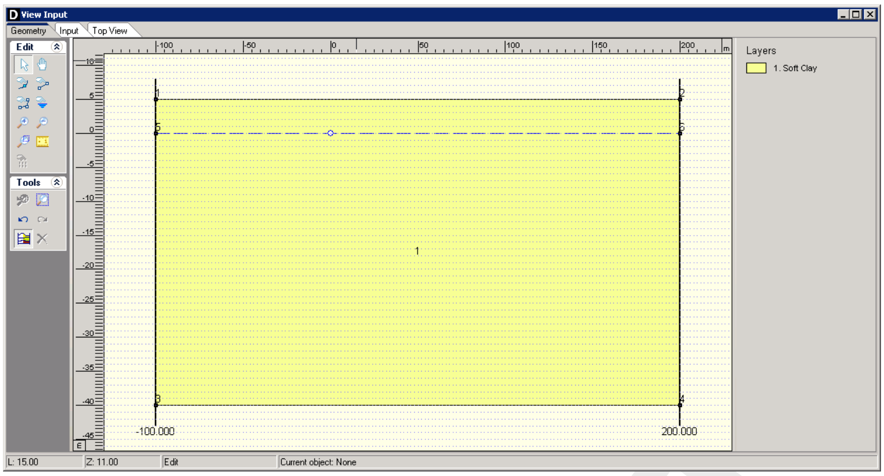


Figure 8.8: *View Input window, Geometry tab*

8.3.1 Soil layer properties

The properties of the soil layers should be specified in the menu materials which can be entered by clicking soil. In this tutorial only one soil layer is considered.

23. Click *Soil* and select *Materials* on the menu bar to open the *Materials* window (Figure 8.9) and enter the soil data.
24. Add a new material by choosing *Add* button below the materials list on the left side of the window with the new <Silty Sand>.
25. Enter the soil data as given in Table 8.1.
26. Finish the input of soil data by clicking *OK*.

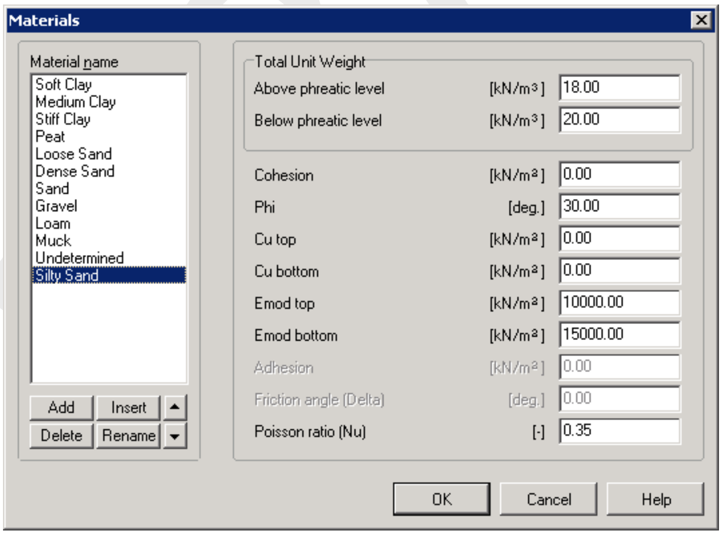


Figure 8.9: *Materials window*

The defined soil properties and the groundwater level have to be assigned to the drawn geometry of the longitudinal cross section. The assignments can be carried out by clicking geometry and choosing the subsequent described options on the menu bar.

8.3.2 Phreatic Line

27. On the *Geometry* menu, select *Phreatic Line* to open *Phreatic Line* window (Figure 8.10) in which the phreatic line for calculation of the groundwater pressures can be selected.
28. Choose PL–line nr. <1> (only one phreatic line is available) and click *OK*.

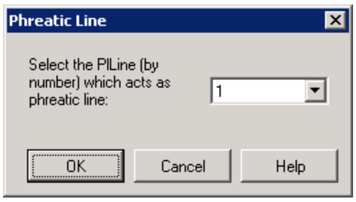


Figure 8.10: *Phreatic Line window*

8.3.3 Layers

29. Click *Geometry* and select *Layers* on the menu bar to assign the soil properties to the soil layers in the longitudinal cross section. To assign a material to a layer, select the *Material* tab.
30. Assign the properties of the defined layer *Silty Sand* to layer number one in the longitudinal cross section. The available soil layers with defined properties are shown in left column of the materials window. The layers in the longitudinal cross section are shown in the right column of the materials window. The defined properties are assigned to layer nr 1 by clicking the arrow in between the columns. This will result in the *Material* tab shown in Figure 8.11.

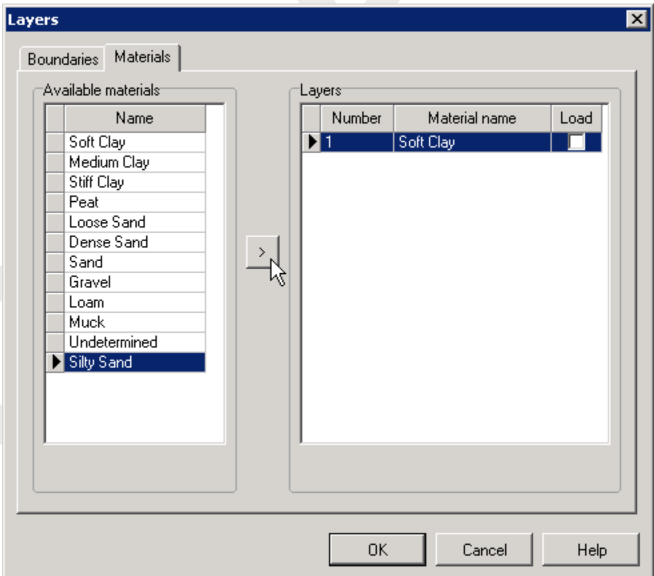


Figure 8.11: *Layers window, Materials tab*

31. Click *OK* to quit the window and return to the geometry window to watch the change of layer name in the legend.

8.3.4 PL-Lines per Layers

32. Click *Geometry* and select *PL–lines per Layers* on the menu bar to open the *PL–lines per Layer* window (Figure 8.12) in which the defined PL–lines to the soil layers in the longitudinal cross section can be defined. This window contains the information for the

calculation of the groundwater pressure distribution. In this tutorial only one PL–line is defined. The groundwater pressure at the top of the silty sand layer and the bottom of this layer should be calculated based on the hydraulic head of PL–line 1.

33. Click *OK* to close the window.

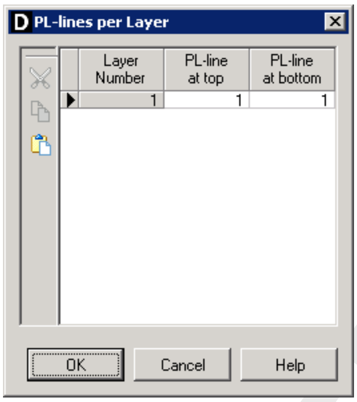


Figure 8.12: *PL-lines per Layers window*

8.3.5 Check Geometry

34. The geometry can be tested by clicking *Geometry* and selecting *Check Geometry* on the D-GEO PIPELINE menu bar. If the geometry is entered properly, the message shown in Figure 8.13 appears.
35. Click *OK* to close the window.

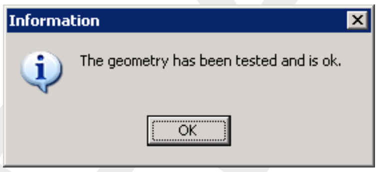


Figure 8.13: *Check Geometry window*

8.4 Pipeline Configuration

36. Click *Pipe* and select *Pipeline Configuration* on the menu bar to open the *Pipeline configuration* window in which the pipeline configuration can be put in.
37. Enter the values given in Figure 8.1 of the introduction.
38. Select a *Pulling direction product pipe* <From left to right> as indicated in Figure 8.14.

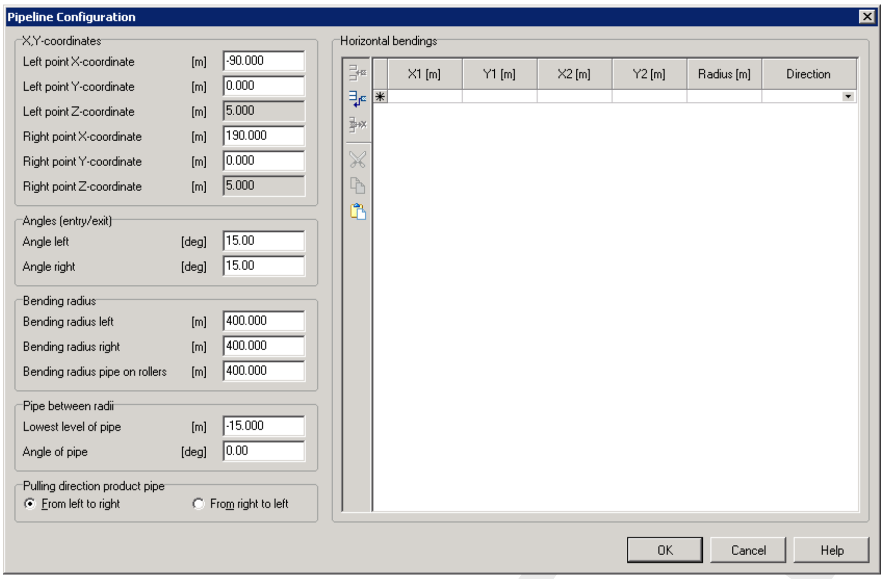


Figure 8.14: Pipeline Configuration window

39. Confirm by clicking *OK*.
40. Watch the entered pipeline configuration on the *Input* tab of the *View Input* window (Figure 8.15).

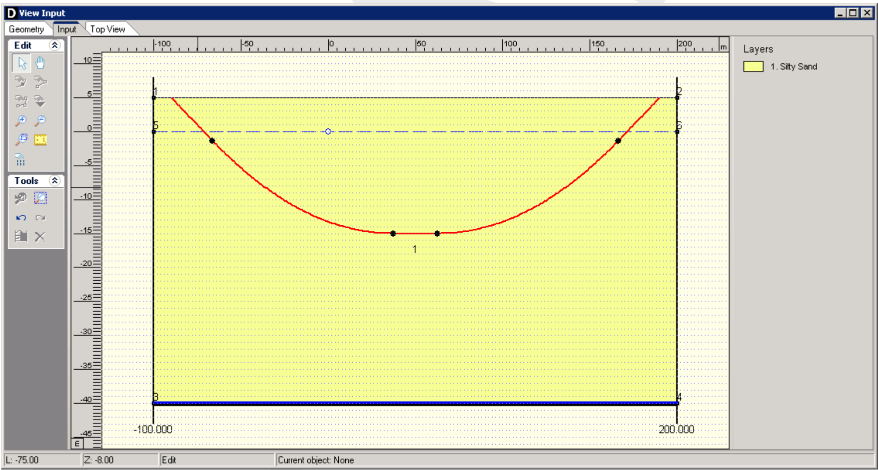


Figure 8.15: View Input window, Input tab

8.5 Soil behavior

When the borehole is created, the drilling fluid will exert pressure on the borehole wall and the soil next to the borehole. When the pressure rises above a certain value, plastic deformation of the soil will occur, initially adjacent to the borehole. When the pressure is increased further beyond this value, the zone with plastic deformation will increase. If the zone with plastic deformation reaches the surface a blow-out will occur. Besides the growth of the plastic zone due to high drilling fluid pressures, formation of cracks in the borehole wall in granular soils will take place before the plastic zone reaches its maximum expansion. The formation of cracks around the borehole in granular soils is dependent on the strain of the bore hole wall which occurs when the drilling fluid pressure is increasing and the borehole is expanding.

Crack formation and growth of the plastic zone are dependent upon soil characteristics. Soil layers with a very high strength and/or a very high stiffness are suitable for drilling with high

drilling fluid pressures.

Strength of soil layers is dependent on the drained or undrained behavior of soil layers during application the drilling fluid pressure on the bore hole wall. Depending on the permeability of the soil layer, the soil will behave drained or undrained. The coarser granular soils are usually well permeable so that the excess water pressure due to the drilling fluid pressures will dissipate easily. The strength of the soil which exhibits this drained behavior can be calculated using the drained (effective) strength parameters effective cohesion (c) and angle of internal friction (φ). In case of undrained behavior, which usually occurs in very fine grained cohesive soils, the strength of the soil should be calculated using the undrained cohesion (c_{u}).

41. Click *GeoObjects* and select *Boundaries Selection* on the menu bar to select the input window specification of the soil behavior. This will result in the *Boundaries Selection* window shown in Figure 8.16.
42. Choose the boundary between the undrained and drained layer on top of layer nr 1. This choice results in drained behavior of layer nr 1. The other in the boundaries window mentioned boundary in between compressible and incompressible layers can be chosen on top of layer nr 1 (see tutorial 3 for explanation about this compressibility boundary).

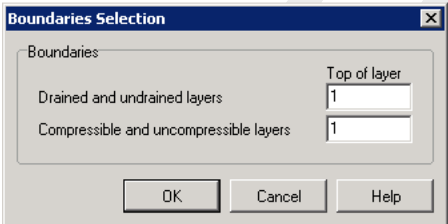


Figure 8.16: *Boundaries Selection window*

8.6 Calculation Verticals

The locations in the longitudinal cross section at which a calculation should be carried out must be specified by the user. The user is able to perform calculations at uniform distances along the longitudinal cross section but is also able to perform more calculations at short distances at areas of interest.

43. Click *GeoObjects* and select *Calculation Verticals* on the menu bar to select the *Calculation Verticals* window for specification of the calculation locations along the longitudinal cross section.
44. Choose the *Automatic generation of L co-ordinates* option on the right side of the window and choose the following values: <–80 m> for *First*, <180 m> for *Last* and <20 m> for *Interval*.
45. Click on the *Generate* button and watch the result of automatic vertical generation on the left side of the *Calculation Verticals* window. This will result in the window shown in Figure 8.17.
46. Click *OK* to confirm the selected verticals and switch to the input window to watch the location of the verticals in the longitudinal cross section.

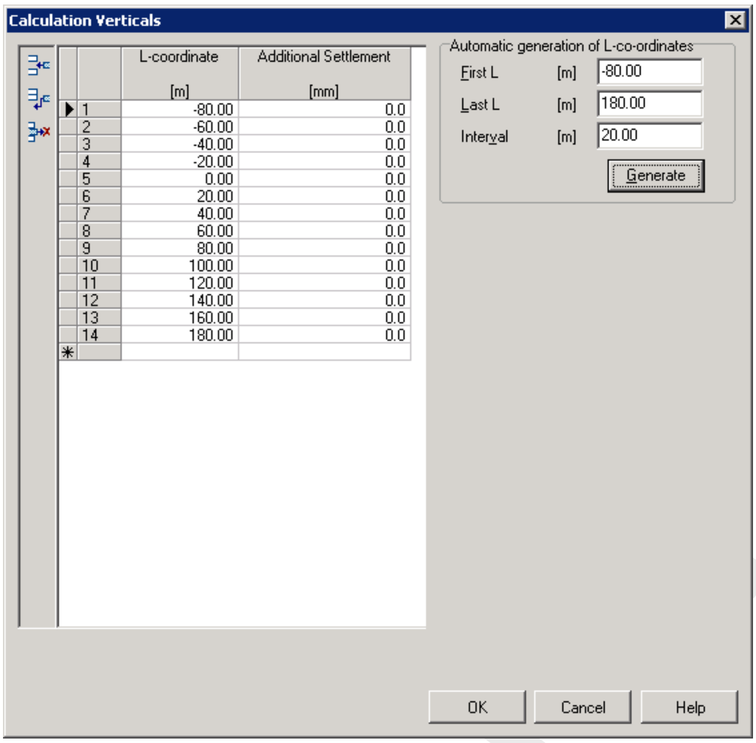


Figure 8.17: *Calculation Verticals window*

8.7 Product Pipe Material Data

The dimensions and the properties of the product pipe which should be installed in the reamed borehole should be specified. Especially the outer diameter is important for the calculation of the drilling fluid pressures during the pull back operation.

47. Click *Pipe* and select *Product Pipe Material Data* on the menu bar to open the *Product Pipe Material Data* window for specification of the dimensions and properties of the product pipe.
48. Click on the button *Add* on the left side of the window to declare a pipeline with the name <Pipe 1>.
49. Enter the values given in Table 8.2 for *Pipe 1* in the fields on the right side of the window as shown in Figure 8.18.
50. Click *OK* to confirm.

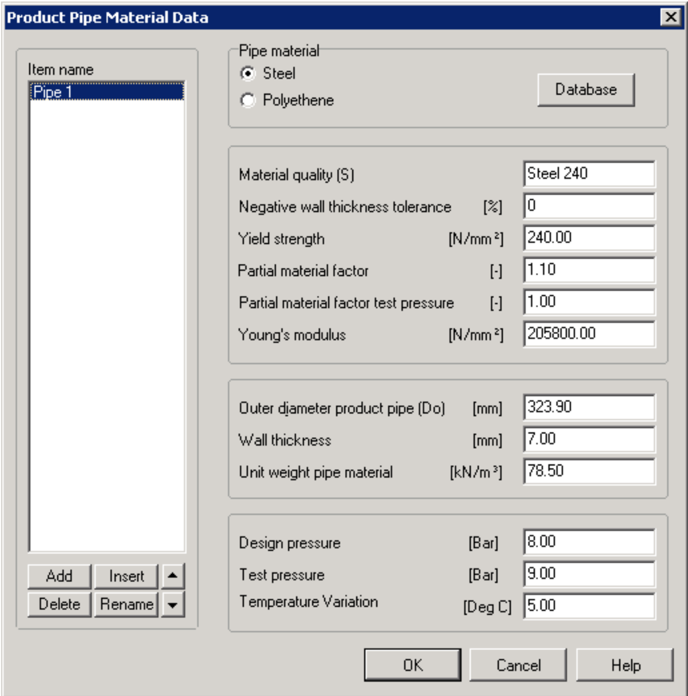


Figure 8.18: *Product Pipe Material Data window*

8.8 Drilling Fluid Data

Various types of drilling fluids exist; the drilling fluid has properties to transport the cuttings from the borehole to the surface. The flow behavior, which depends on the drilling fluid properties, is an important characteristic for the development of drilling fluid pressure during the different drilling stages.
Generally, the flow behavior of drilling fluid can be described with the Bingham model. The Bingham model is used in D-GEO PIPELINE and describes the fluid by means of a viscosity term and a threshold term from which flow is initialized. The threshold is called the yield point.
D-GEO PIPELINE calculates the required minimum fluid pressure at the calculation verticals.
During all stages of the drilling process, a pipe is present in the borehole, drill pipe or product pipe. The return flow of drilling fluid with cuttings occurs in the annulus between the borehole wall and the pipe. The required fluid pressure to initiate flow depends on the width of the annulus (radius borehole minus radius drill pipe), the properties of the drilling fluid and the required annular fluid flow rate.

The properties of the drilling fluid and the operation parameter values should be specified in D-GEO PIPELINE.

51. Click *Pipe* on the menu bar and select *Drilling Fluid Data* to open the *Drilling Fluid Data* window for specification of properties of the drilling fluid and the operation parameter values.
52. Enter the values given in Figure 8.19.
53. Click *OK* to confirm the input.

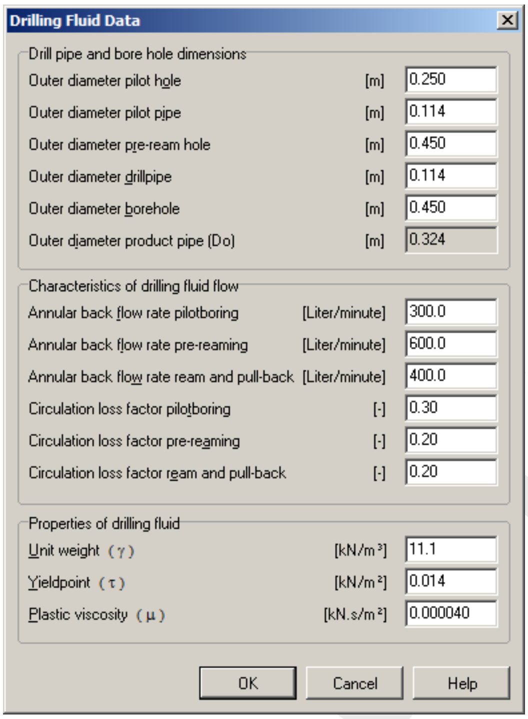


Figure 8.19: *Drilling Fluid Data window*

8.9 Factors

D-GEO PIPELINE performs the calculations of the maximum allowable drilling fluid pressures according the Dutch regulations described in the NEN 3650 and 3651. The safety philosophy described in the NEN 3650-1 Annex B and D (NEN, 2012a) is applied on the calculations.

54. Click *Defaults* on the menu bar and select *Factors* to open the *Factors* window in which the default values of the contingency and safety factors are shown and can be modified. Since the window shown in Figure 8.20 shows all factors according to the Dutch regulations adapting the values is not necessary.
55. Click *OK* to confirm.

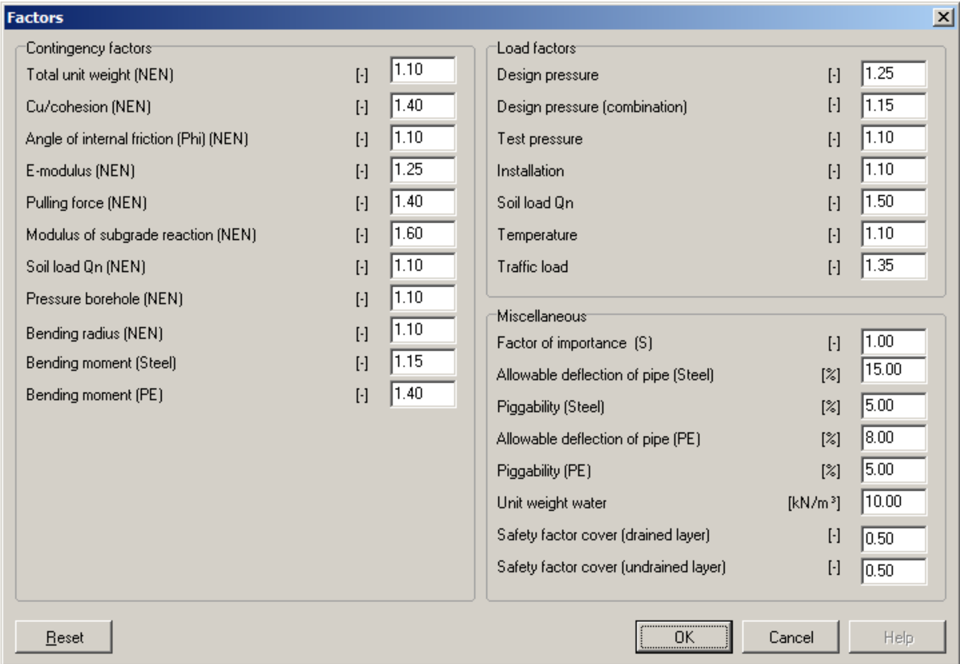


Figure 8.20: *Factors window*

8.10 Results

The calculation of the drilling fluid pressures during the three stages of installation of the steel pipe using the horizontal directional drilling technique can be started from the D-GEO PIPELINE menu.

56. Click *Calculation* and select *Start* on the menu bar to start the calculation or press the function key F9. D-GEO PIPELINE automatically saves the file during the calculation.
57. Click *Results* and select *Drilling fluid pressure plots* on the menu bar to watch the results of the drilling fluid pressure calculations for the pilot drilling. The window shown in Figure 8.21 will appear. The graph shows the maximum allowable pressures (upper limit related to soil cover and lower limit related to deformation of the borehole) and the minimal required drilling fluid pressure for transportation of the cuttings.

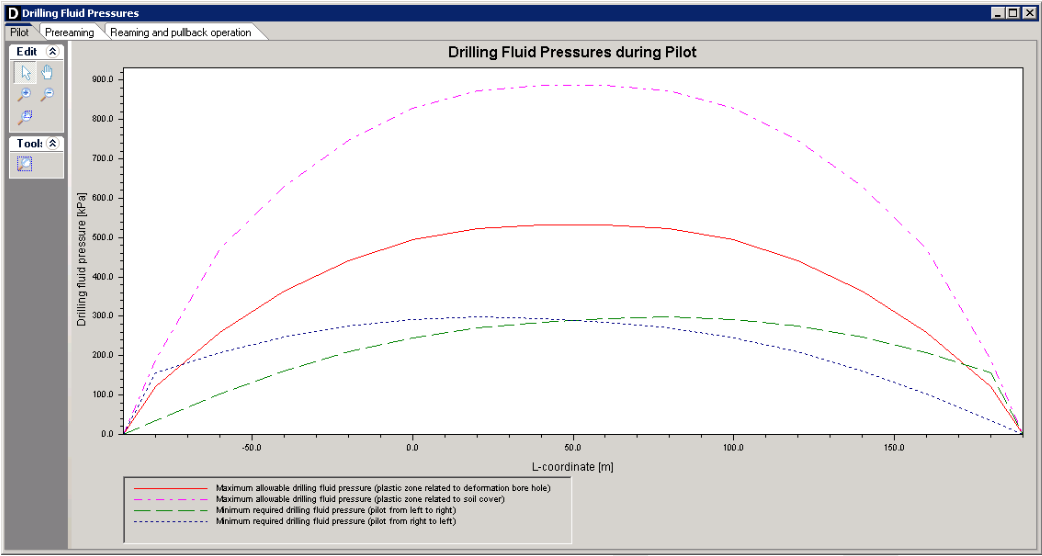


Figure 8.21: *Drilling Fluid Pressures window*

58. Click on the tabs *Prereaming* and *Reaming and pullback* to watch the results of the other drilling stages.
59. Close the window to return to the main window.

Notice that the minimal required drilling fluid pressure is lower than the maximal allowable drilling fluid pressure in the pilot drilling stage. The risk on a blow out is therefore very small. Of course, due to the decreasing soil cover, the last meters of the pilot drilling the minimal required drilling fluid pressure is higher than the allowable drilling fluid pressure, but in this situation the distance where the minimal required drilling fluid is higher than the maximum allowable pressure is very small.

8.11 Conclusion

Various input windows are used to enter the details of a project that is to be modeled and analyzed. Once these details have been put in, they can be used to calculate a range of results, including drilling fluid pressures during the three stages of the HDD technique. One way to view these results is to display them graphically on the screen.

9 Tutorial 2: Stress analysis of steel pipes and polyethylene pipes

This second exercise considers installation of a steel pipeline and installation of a polyethylene pipeline by using the technique horizontal directional drilling. The exercise focuses on the stress analysis for the different installation stages, which is required to assess whether installation of the pipeline according the design is executable or not.

The objectives of this tutorial are:

- ◇ To calculate the pulling force on the pipeline during the pull back operation.
- ◇ To calculate the stresses in the pipeline during the different installation stages.
- ◇ Assessment of the calculated stresses in the pipeline.
- ◇ To perform a Special Stress Analysis.
- ◇ To perform a calculation for a polyethylene pipe.

The following module is needed:

- ◇ D-GEO PIPELINE Standard module (HDD)

This tutorial is presented in the files Tutorial-2a.dri, Tutorial-2b.dri and Tutorial-2c.dri.

9.1 Introduction to the case

The pipeline configuration and the soil type is the same as those modeled in the first tutorial (Figure 9.1).

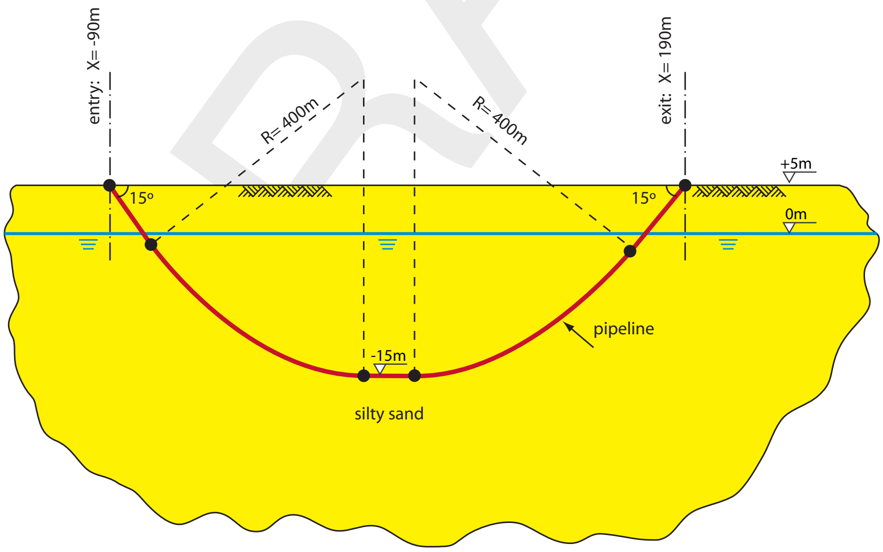


Figure 9.1: *Pipeline configuration for Tutorial 2*

Different calculations will be performed using two pipe materials:

- ◇ A steel pipe with the properties given in Table 9.1 (Tutorial 2a),
- ◇ The same pipe as Tutorial 2a, but performing a *Special Stress Analysis* (Tutorial 2b).
- ◇ A polyethylene pipe with the properties given in Table 9.1 (Tutorial 2c).

Table 9.1: *Pipe properties (Tutorial 2)*

		Tutorials 2a / 2b	**Tutorial 2c**
Pipe material		Steel	Polyethylene
Material quality		Steel 355	PE 100
Negative wall thickness tolerance	[%]	0	n.a.
Young's modulus	[N/mm^2]	205800	1200
Young's modulus (long term)	[N/mm^2]	n.a.	300
Allowable/Yield strength	[N/mm^2]	355	10
Allowable strength (long term)	[N/mm^2]	n.a.	8
Partial material factor	[-]	1.1	n.a.
Partial material factor test pressure	[-]	1	n.a.
Tensile factor	[-]	n.a.	0.65
Outer Diameter	[mm]	323.9	400
Wall thickness	[mm]	8	36.4
Unit weight pipe material	[kN/m^3]	78.5	9.54
Design pressure	[Bar]	8	4
Test pressure	[Bar]	9	5
Temperature variation	[°C]	5	5

In the first tutorial, the assessment whether the proposed drilling line and borehole dimensions according the design is executable or not was performed. The second tutorial considers the assessment of stresses in pipeline during the different installation stages and after installation.

In D-GEO PIPELINE it is assumed that the pipeline remains fixed at the specified location and that settlement of the soil layers below the pipeline does not influence the pipeline. Therefore a relative simple pipe stress analysis can be performed.

The first installation stage at which the stresses in the pipeline are considered is the start of the pull back operation. The pipeline with the connected pullback equipment is situated on the rollers. Often the pipeline is not filled with water on the rollers in order to reduce the required pulling force to pull the pipeline over the rollers. Of course when the pipeline enters the borehole filling of a part of the pipeline (percentage of the cross section area) is sometimes useful.

In this stage a pulling force is exerted on the pipe, which results in axial stress in the pipeline. Near the exit point, the rollers are often configured with a certain bending radius (the so-called overbend), so that additional axial stresses occur due to bending. The tangential stresses for the pipeline on the rollers are negligible.

The second stage at which the stresses in the pipeline are considered is the maximum pulling force situation during the pull back operation. At the end of the pull back operation the pulling force usually reaches the maximum pulling force. The pulling force is calculated according the Dutch regulations described in NEN 3650 and is mainly based on the normal forces of the pipeline perpendicular to the borehole wall. The normal forces are caused by the buoyant weight of the pipeline and soil reaction forces due to the bending moment in the pipeline in the bends of the drilling line. In the second stage both the axial stresses due to pulling and bending are calculated and the tangential stresses due to soil reaction forces are calculated.

The third stage at which the stresses in the pipeline are considered is the long term stage after installation. When the pipeline is installed, a situation without internal pressure and a situation with internal pressure are considered. In this final stage the drilling fluid in the borehole is

assumed to be consolidated, so that the contribution of soil pressure on the pipeline is taken into account for the calculation of the tangential stress.

The stresses in the pipeline are calculated for the different installation stages. According NEN 3650 an additional calculation is made for application of internal pressure on the pipeline. Therefore in the stress analysis according the NEN 3650, four Load Combinations (LC) are considered:

- ◇ LC 1A: start of the pullback operation
- ◇ LC 1B: end of the pullback operation
- ◇ LC 2: application of internal pressure on the pipeline
- ◇ LC 3: pipeline after installation, without internal pressure
- ◇ LC 4: pipeline after installation, with internal pressure

The calculated stresses are assessed according NEN 3650 for the steel pipelines and according NEN 3652 for the polyethylene pipelines.

9.2 Project Properties

This tutorial is based on continuation of the file used in Tutorial 1 (chapter 8).

1. Click *File* and select *Open* on the menu bar to select the *Open* window for the choice of the D-GEO PIPELINE file created at the end of tutorial 1.
2. Select *Tutorial–1* and click the *Open* button to open de file.
3. Click *File* and select *Save as* on the menu bar to select the save file window and rename the file into <Tutorial–2a>.
4. Click the *Save* button to save the file for Tutorial 2a.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 2 for D-GEO PIPELINE > and <Stress analysis of steel and polyethylene pipes> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

9.3 Product Pipe Material Data

The dimensions and the properties of the product pipe which should be installed in the reamed borehole should be specified for a pipe stress analysis.

8. Click *Pipe* on the menu bar and select *Product Pipe Material Data* to open the *Product Pipe Material Data* window for specification of the dimensions and properties of the product pipe.
9. For *Pipe 1*, enter the values given in Figure 9.2.
10. Click *OK* to confirm the specified product pipe material data.

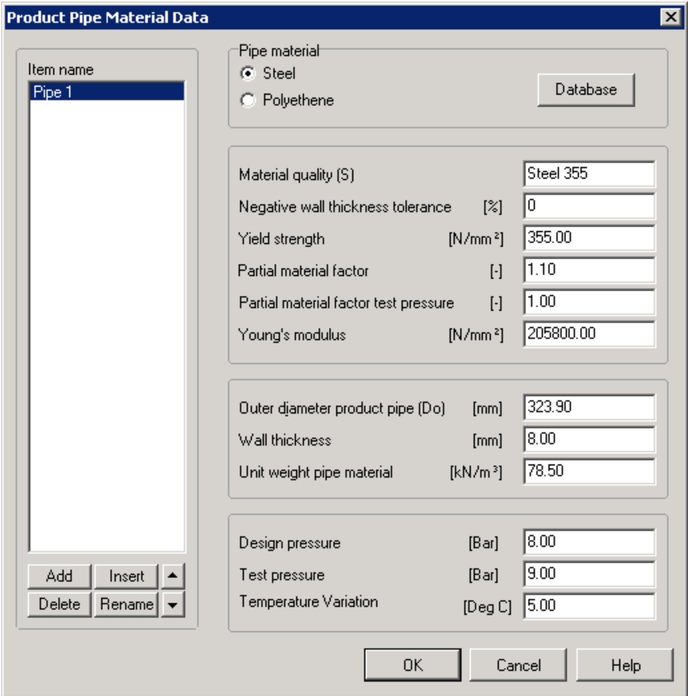


Figure 9.2: *Product Pipe Material Data window*

9.4 Engineering Data

The first step of the pipe stress analysis is the calculation of the pulling force. The magnitude of the pulling force plays an important role in the stress distribution in the pipe during the pill back operation. The pulling force is calculated according the specifications described in NEN 3650.

During the pull back operation the moving pipeline contacts the wall of the borehole and pushes with a certain forces perpendicular to the wall of borehole. These perpendicular forces (normal forces) determine the magnitude of the shear force in axial direction during the pull back operation.

In order to reduce the normal forces on the borehole wall the pipeline is sometimes ballasted during the pull back operation. In the part of the HDD without significant bends, the distribution of the normal forces on the bore hole wall is determined by the effective weight of the pipeline. The effective weight is defined as follows:

$$g_{\text{eff}} = g - g_{\text{uplift}} \tag{9.1}$$

with:

$$g_{\text{uplift}} = \pi \times r_{\text{e}}^2 \times \gamma_{\text{df}} \tag{9.2}$$

where:

r_{e}	is the outer radius of the pipeline, in m;
g_{uplift}	is the upward force of the pipeline, in kN/m;
g	is the weight of the ballasted pipeline, in kN/m;
γ_{df}	is the unit weight of the drilling fluid, in kN/m^3.

Using the above described equation it can be calculated that filling the product pipe for 22 % results in a nearly weightless pipe in the bore hole. Of course it is wise not to fill the product pipe on the rollers so that the pulling force during the first part of the pull back operation can be reduced.

11. Click *Pipe* and select *Engineering Data* on the menu bar to open the *Engineering Data* window.
12. Do not mark the *Pipe filled with water on rollers* check-box and enter the values given in Figure 9.3.
13. Click on the *OK* button to confirm the input of the specified values.

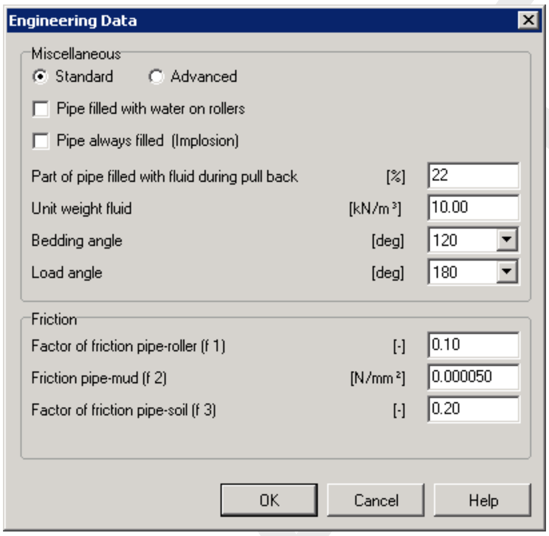


Figure 9.3: *Engineering Data window*

The bedding (β) and the load angle (α) are shown in Figure 9.4. The values are used in the pipe stress analysis to determine the moment coefficients.

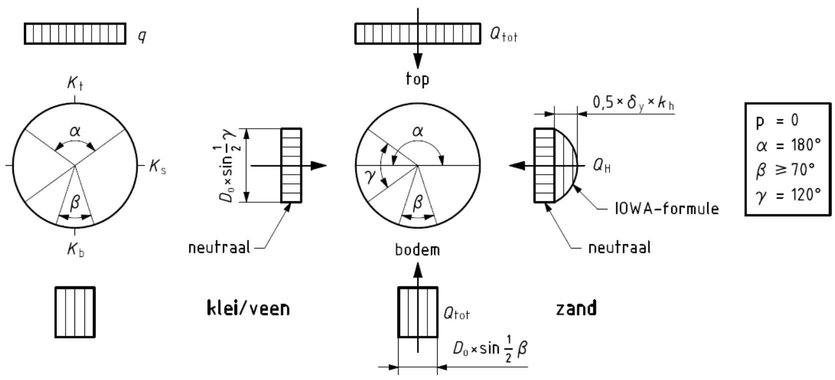


Figure 9.4: *Bedding and load angles on the pipeline (according to Figure D.2 of NEN 3650-1)*

9.5 Factors

D-GEO PIPELINE performs the calculations for the pipe stress analysis according the Dutch regulations described in the NEN 3650 and 3651. The safety philosophy described in Annex B and D of the NEN 3650-1 (NEN, 2012a) is applied on the calculations.

14. Click *Defaults* on the menu bar and select *Factors* to open the *Factors* window for watching the default values or for alternating these values. Since the window shown in Figure 9.5 shows all factors according the Dutch regulations adapting the values is not necessary.
15. Click *OK* to confirm.

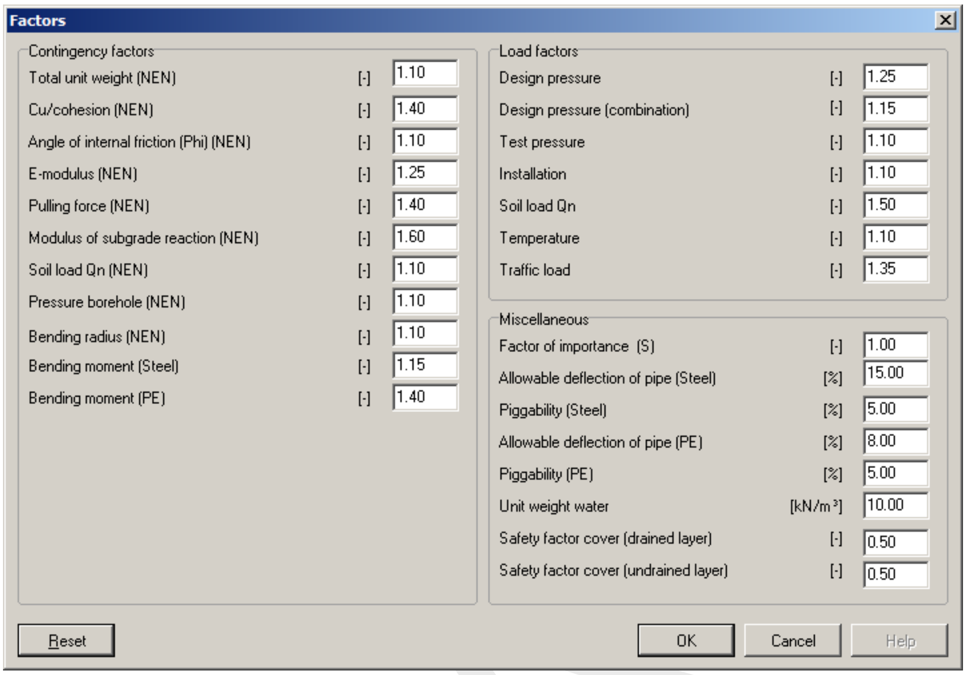


Figure 9.5: *Factors window*

9.6 Calculation and Results (Tutorial-2a)

The results of the pulling force calculation are shown in the D-GEO PIPELINE report which is created automatically after finishing the calculations.

16. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.

9.6.1 Results of the pulling force calculation

17. Click *Results* and select *Report* on the menu bar to look at the results of the pulling force calculation. The results can be found in paragraph 5.3 (Figure 9.6).

5.3 Calculation Pulling Force

During the pullback operation the pipe experiences friction which is based on:

- friction between pipe and pipe-roller (f1 = 0.10)
- friction between pipe and drilling fluid (f2 = 0.000050 [N/mm²])
- friction between pipe and soil (f3 = 0.20)

Due to the friction a pulling force is induced in the pipeline.
The pulling direction of the product pipe is from left to right

This calculation takes into account that the length of the pipe on the rollers decreases while pulling back the pipeline. During the pull back operation the bore hole is supposed to be stable.

Characteristic points	Length pipe in bore hole (m)	Expected pulling force (kN)
T1	0	18
T2	25	18
T3	129	35
T4	155	35
T5	259	53
T6	284	54

The calculated pulling force is the mean value. It is recommended to use a contingency factor of at least 1.4 for the stress analysis. In the subsequent pipe stress analysis a factor of 1.40 is used and a load factor of 1.10 (steel only).

The maximum representative pulling force is 3434 kN, calculation factor excluded. At this pulling force level the stresses in the pipeline are equal to the yield strength.

Figure 9.6: *Report window, Calculation pulling force (filling percentage = 22%)*

18. In Figure 9.7 the characteristic locations along the drilling line at which the pulling force is calculated are shown. Notice that the maximum pulling force is 54 kN.

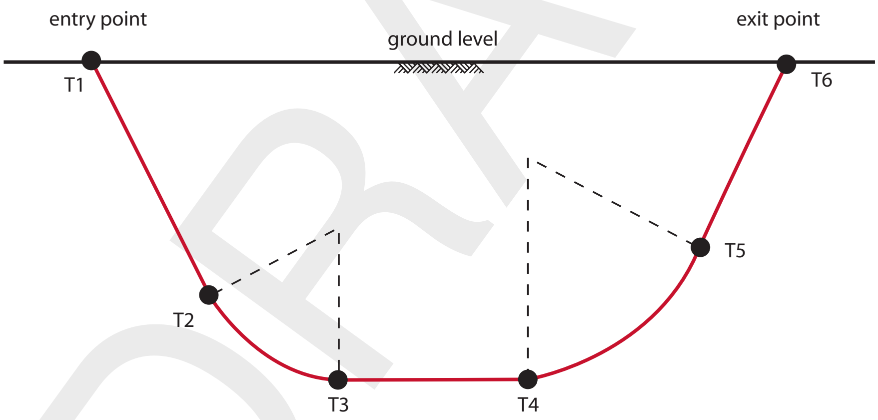


Figure 9.7: *Schematic overview of the characteristic points*

19. Switch back and click *Pipe* and select *Engineering Data* on the menu and alter the *Part of pipe filled with fluid during pull back* to $<$0%$>$.
20. Start the calculations again by clicking *Calculation* and select *Start* on the menu bar or by pressing the function key F9.
21. Click *Results* and select *Report* on the menu bar to watch the results of the pulling force calculation. Notice that the pulling force has increased to 64 kN (Figure 9.8).

5.3 Calculation Pulling Force

During the pullback operation the pipe experiences friction which is based on:

- friction between pipe and pipe-roller (f1 = 0.10)
- friction between pipe and drilling fluid (f2 = 0.000050 [N/mm²])
- friction between pipe and soil (f3 = 0.20)

Due to the friction a pulling force is induced in the pipeline.
The pulling direction of the product pipe is from left to right

This calculation takes into account that the length of the pipe on the rollers decreases while pulling back the pipeline. During the pull back operation the bore hole is supposed to be stable.

Characteristic points	Length pipe in bore hole (m)	Expected pulling force (kN)
T1	0	18
T2	25	19
T3	129	39
T4	155	41
T5	259	62
T6	284	64

The calculated pulling force is the mean value. It is recommended to use a contingency factor of at least 1.4 for the stress analysis. In the subsequent pipe stress analysis a factor of 1.40 is used and a load factor of 1.10 (steel only).

The maximum representative pulling force is 3434 kN, calculation factor excluded. At this pulling force level the stresses in the pipeline are equal to the yield strength.

Figure 9.8: *Report window, Calculation pulling force (filling percentage = 0%)*

9.6.2 Results of the pipe stress analysis of the steel pipe

The pipe stress analysis is described in the report. For each load combination the axial and tangential stresses in the product pipe are calculated. The stresses are used to calculate the maximum combined stress in the pipeline.

22. Click *Results* and select *Report* on the menu bar to watch the results of the calculated axial and tangential stresses for each load combination/installation stage in paragraph 6.2 (see Figure 9.9).

6.2 Results Stress Analysis of Pipe: Pipe 1

In the calculation 5 load combinations are considered:

- Load combination 1A: start pull-back operation
- Load combination 1B: end of pull-back operation
- Load combination 2: application internal pressure
- Load combination 3: pipeline in operation, no inner pressure
- Load combination 4: pipeline in operation, pressure applied

The nominal wall thickness is 8.0 mm. The calculation hereafter will prove that the pipeline wall thickness is sufficient. The calculations are in accordance with NEN 3650 and NEN 3651.

6.2.1 Load Combination 1A: Start Pullback Operation

Axial stress:

Sigma_b = Mb/Wb = f_k.E·Ib/(Rrol·Wb)	=	96	[N/mm²]
Sigma_t = f_pull * T1/A	=	3	[N/mm²]
Maximum axial stress Sigma_a,max	=	99	[N/mm²]

In this load combination the tangential stress is negligible.

Figure 9.9: *Report window, Results Stress Analysis (Tutorial-2a)*

23. Continue looking at the report and scroll down to paragraph 6.3. In the table in paragraph 6.3, the stress assessment is carried out: the calculated stresses are compared with the yield strength of steel according to the specifications described in NEN 3650. Below the stress assessment table, the results of the deflection calculation are given (see

Figure 9.10).

6.3 Check on Calculated Stresses of Pipe: Pipe 1

According to NEN 3650-2 art.5 D.3.1 the calculated stresses for the load combinations, must meet the following conditions (note: Re = 355 [N/mm²]) :

Load combination 1
Sigma_v =< Re/Gamma_m

Load combination 2
- Sigma_ptest =< Re/Gamma_test
- Sigma_py =< Re/Gamma_m
- Sigma_pm =< 1.1·Re/Gamma_m

Load combinations 3 and 4
- Sigma_vmax =< 0.85(Re+Re_20deg)/Gamma_m

All stresses in all conditions are allowable.

	Max allowable stress [N/mm²]	Load combination1A	Load combination1B	Load combination2	Load combination3	Load combination4
Sigma_v	322.73	99	112	-	-	-
Sigma_ptest	355.00	-	-	20	-	-
Sigma_py	322.73	-	-	20	-	-
Sigma_pm	355.00	-	-	17	-	-
Sigma_vmax	548.64	-	-	-	135	135

Stresses in pipeline [N/mm²]

The deflection of the pipeline is 0.6 mm (0.20% x Do). The maximum allowable deflection of the pipeline is 16.2 mm (5.00% x Do). The deflection is allowable..
For piggability the maximum allowable deflection of the pipeline is 16.2 mm (5.00% x Do). The deflection is allowable..

Figure 9.10: *Report window, Check on calculated stresses (Tutorial-2a)*

24. Notice that the calculated stresses for all load combinations are allowable. The deflection is lower than the allowable value.
25. Look at the calculated soil load and the calculated modulus of subgrade reaction on paragraph 4.1.

4 Soil Mechanical Parameters

4.1 Soil Mechanical Parameters (Pipe: Pipe 1)

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m²
Pv;n	Neutral soil load	kN/m²
Ph;n	Neutral horizontal soil load	kN/m²
Pv,r;n	Reduced neutral soil load	kN/m²
kv,top1	Vertical modulus of subgrade reaction (bilinear) upward	kN/m³
kv,top2	Vertical modulus of subgrade reaction upward	kN/m³
dv	Vertical displacement	mm
kv	Vertical modulus of subgrade reaction downward	kN/m³
Pv;e	Vertical bearing capacity	kN/m²
kh	Horizontal modulus of subgrade reaction	kN/m³
Ph;e	Horizontal bearing capacity	kN/m²
tmax	Maximal friction pipe-drilling fluid	kN/m²
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m²]	Pv;n [kN/m²]	Ph;n [kN/m²]	Pv,r;n [kN/m²]	kv,top [kN/m³]
1	151	46	34	46	13722
2	596	119	13	18	14558
3	754	163	12	16	15265
4	866	197	11	15	15805
5	941	221	11	15	16183
6	984	235	11	15	16400
7	996	239	11	15	16460
8	996	239	11	15	16460
9	984	235	11	15	16400
10	941	221	11	15	16183
11	866	197	11	15	15805
12	754	163	12	16	15265
13	596	119	13	18	14558
14	151	46	34	46	13722

Vertical nr.	dv [mm]	kv [kN/m³]	Pv;e [kN/m²]	kh [kN/m³]	Ph;e [kN/m²]	tmax [kN/m²]	dmax [mm]
1	0	14028	1298	9819	267	0.05	8
2	0	14865	3194	10405	596	0.05	8
3	0	15572	4391	10901	754	0.05	8
4	0	16113	5303	11279	866	0.05	8
5	0	16492	5939	11544	941	0.05	8
6	0	16709	6305	11696	984	0.05	8
7	0	16769	6405	11738	996	0.05	8
8	0	16769	6405	11738	996	0.05	8
9	0	16709	6305	11696	984	0.05	8
10	0	16492	5939	11544	941	0.05	8
11	0	16113	5303	11279	866	0.05	8
12	0	15572	4391	10901	754	0.05	8
13	0	14865	3194	10405	596	0.05	8
14	0	14028	1298	9819	267	0.05	8

Maximum soil load	:	Pv;n, max = 239 kN/m²
Maximum reduced soil load	:	Pv,r;n, max = 46 kN/m²
Maximum vertical modulus of subgrade reaction (without safety factor)	:	kv, max = 16769 kN/m³
Maximum vertical modulus of subgrade reaction (with safety factor)	:	kv, max = 33931 kN/m³

Figure 9.11: *Report window, Soil Mechanical Parameters (Tutorial-2a)*

9.7 Special Pipe Stress Analysis (Tutorial-2b)

The option special stress analysis can be used for a pipe stress analysis in case of additional loads at certain location along the longitudinal cross section. Additional loads can for example be induced by traffic or by constructions.

Assume that vertical 1 is located below a highway which will result in an additional load on the pipeline. The load induced by soil stress is already calculated by D-GEO PIPELINE and is assessed in the report (see section 9.6.2). The additional load at the depth of the pipeline can be determined using load distribution theories.

26. Click *File* and select *Save As* on the menu bar to select the *Save As* window and rename the file into <Tutorial-2b>.
27. Click the *Save* button to save the file for Tutorial-2b.
28. Click *Defaults* and select *Special Stress* on the menu bar to open the *Special Stress Analysis* window and enter the data for the special pipe stress analysis. In this window (Figure 9.12), the soil load enhanced with the traffic load should be specified. The reduced

soil load equals <18 kN/m^2> and the modulus of subgrade reaction is independent of the load and remains <17000 kN/m^3>. The radius is the same as defined in the pipeline configuration <400 m>.

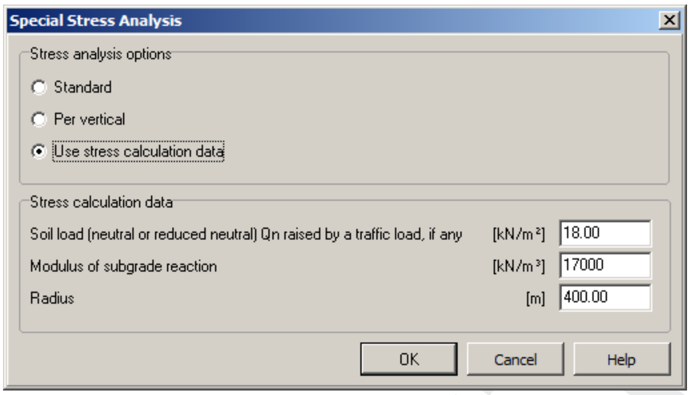


Figure 9.12: *Special Stress Analysis window*

29. Click *OK* to confirm.
30. Click *Calculation* and select *Special Stress Analysis* on the menu bar to start the calculation.
31. Click *Results* and select *Report* on the menu bar to look at the results on paragraph 4.3 (see Figure 9.13). Notice the difference with Figure 9.10 for Tutorial-2a.

4.3 Check on Calculated Stresses of Pipe: Pipe 1

According to NEN 3650-2 art.5 D.3.1 the calculated stresses for the load combinations, must meet the following conditions (note: Re = 355 [N/mm²]) :

Load combination 1
Sigma_v =< Re/Gamma_m

Load combination 2
- Sigma_ptest =< Re/Gamma_test
- Sigma_py =< Re/Gamma_m
- Sigma_pm =< 1.1·Re/Gamma_m

Load combinations 3 and 4
- Sigma_vmax =< 0.85(Re+Re_20deg)/Gamma_m

All stresses in all conditions are allowable.

	Max allowable stress [N/mm²]	Load combination1A	Load combination1B	Load combination2	Load combination3	Load combination4
Sigma_v	322.73	99	110	-	-	-
Sigma_ptest	355.00	-	-	20	-	-
Sigma_py	322.73	-	-	20	-	-
Sigma_pm	355.00	-	-	17	-	-
Sigma_vmax	548.64	-	-	-	111	112

Stresses in pipeline [N/mm²]

The deflection of the pipeline is 0.3 mm (0.09% x Do). The maximum allowable deflection of the pipeline is 16.2 mm (5.00% x Do). The deflection is allowable..
For piggability the maximum allowable deflection of the pipeline is 16.2 mm (5.00% x Do). The deflection is allowable..

Figure 9.13: *Report window, Check on calculated stresses (Tutorial-2b)*

9.8 Polyethylene Product Pipe (Tutorial-2c)

Besides a pipe stress analysis on steel pipes a pipe stress analysis on PE-pipes can be carried out using D-GEO PIPELINE.

32. Click *File* and select *Save As* on the menu bar to select the *Save As* window and rename the file into <Tutorial-2c>.

33. Click the *Save* button to save the file for Tutorial-2c.
34. Click *Pipe* and select *Product Pipe Material Data* on the menu bar to open the *Product Pipe Material Data* window for specification of the dimensions and properties of the product pipe.
35. Select *Polyethylene* as *Pipe material* for Pipe 1.
36. Enter the values given in Table 9.1.
37. Click *OK* to confirm.

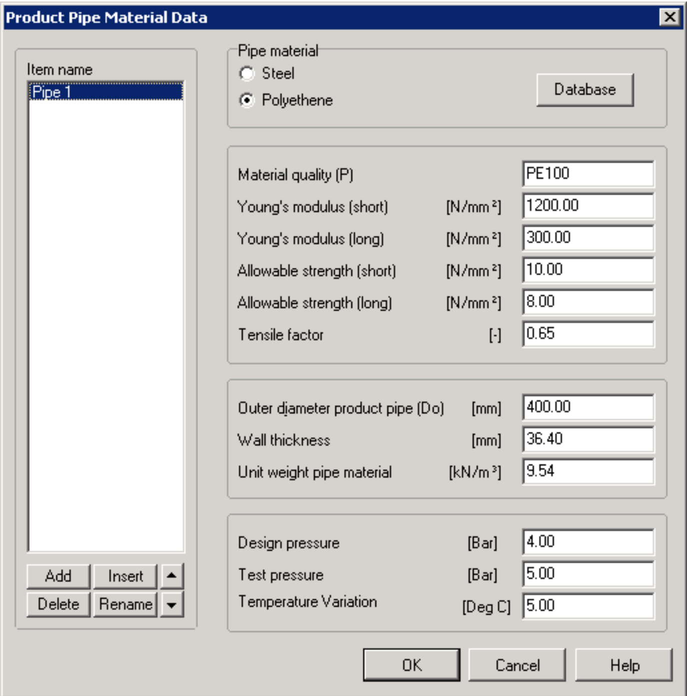


Figure 9.14: *Product Pipe Material Data window (Tutorial-2c)*

38. To start the calculations, click *Calculation* and select *Start* on the menu bar or press the function key F9.
39. Click *Results* and select *Report* on the menu bar to look at the results of the calculated axial and tangential stresses for each load combination/installation stage in paragraph 6.2.
40. Continue looking at the report and scroll down to paragraph 6.3. In the table (Figure 9.15), the stress assessment is carried out: the calculated stresses are compared with allowable stresses according to the specifications described in the NEN 3650 series.

6.3 Check on Calculated StressesPipe: Pipe 1

Load combination 1
- Sigma_AxMax < ShortStrength * DamageFactor
- Sigma_TanMax < ShortStrength * DamageFactor

Load combination 2
- Sigma_ptest < ShortStrength * DamageFactor
- Sigma_py < LongStrength * DamageFactor

Load combination 3
- Sigma_AxMax < LongStrength * DamageFactor
- Sigma_TanMax < LongStrength * DamageFactor

Load combination 4
- Sigma_AxMax < LongStrength * DamageFactor
- Sigma_TanMax < LongStrength * DamageFactor

All stresses in all conditions are allowable.

	Max allowable stress [N/mm²]	Load combination1A	Load combination1B	Load combination2	Load combination3	Load combination4
Sigma_ptest	10.00 (short)	-	-	2.5	-	-
Sigma_py	8.00 (long)	-	-	2.0	-	-
Sigma_axial	10.00 (short)	0.9	3.3	-	-	-
Sigma_axial	8.00 (long)	-	-	-	0.1	1.1
Sigma_tang...	10.00 (short)	-	0.1	-	-	-
Sigma_tang...	8.00 (long)	-	-	-	1.5	3.1

Stresses in pipeline [N/mm²]

The deflection of the pipeline is 2.6 mm (0.6% x Do). The maximum allowable deflection of the pipeline is 32.0 mm (8.0% x S x Do). The deflection is allowable.
For piggability the maximum allowable deflection of the pipeline is 20.0 mm (5.0% x Do). The deflection is allowable..

Figure 9.15: *Report window, Check on calculated stresses (Tutorial-2c)*

41. Below the assessment table in paragraph 6.3, a check on short term and long term implosion is described (see paragraph 6.4 in Figure 9.16). Notice that the short term implosion check is based on the drilling fluid pressure during the pull back operation. The long term implosion check is based on the water pressure at the level of the pipeline.

6.3.4 Check for ImplosionPipe: Pipe 1

During the pullback operation the drilling fluid gives an external pressure. The highest minimum required drilling fluid pressure during the pullback operation is 249 kN/m², this is less than the maximum allowable external pressure of 1911 kN/m².

In operation the water pressure at the lowest point of the drilling gives an external pressure. The maximum water pressure equals 150 kN/m², this is less than the maximum allowable external pressure of 239 kN/m².

Figure 9.16: *Report window, Check for Implosion (Tutorial-2c)*

9.9 Conclusion

This second tutorial analyzes the strength calculations during different stages of the HDD technique for steel and polyethylene pipes. In both cases, the report shows that all stresses for the different stages are allowable.

10 Tutorial 3: Influence of soil behavior on drilling fluid pressures and soil load on the pipe

This third exercise considers installation of a polyethylene pipeline by using the technique horizontal directional drilling. The exercise focuses on the soil behavior and elucidates the effect of drained and undrained soil layers on the calculation of the drilling fluid pressures and elucidates the effect of compressible and incompressible layers on the calculation of the soil load on the pipeline.

The objectives of this tutorial are:

◇ To calculate the drilling fluid pressures for a layered soil sequence;
◇ To calculate the soil load for a layered soil sequence;
◇ Schematization of a layered soil sequence with artesian groundwater.

The following module is needed:

◇ D-GEO PIPELINE Standard module (HDD)

This tutorial is presented in the file Tutorial-3.dri.

10.1 Introduction to the case

This tutorial is based on continuation of the file used in Tutorial-2c (chapter 9). The steel pipe is the same but the layered soil sequence is different as shown in Figure 10.1. The properties of the two layers are given in Table 10.1.

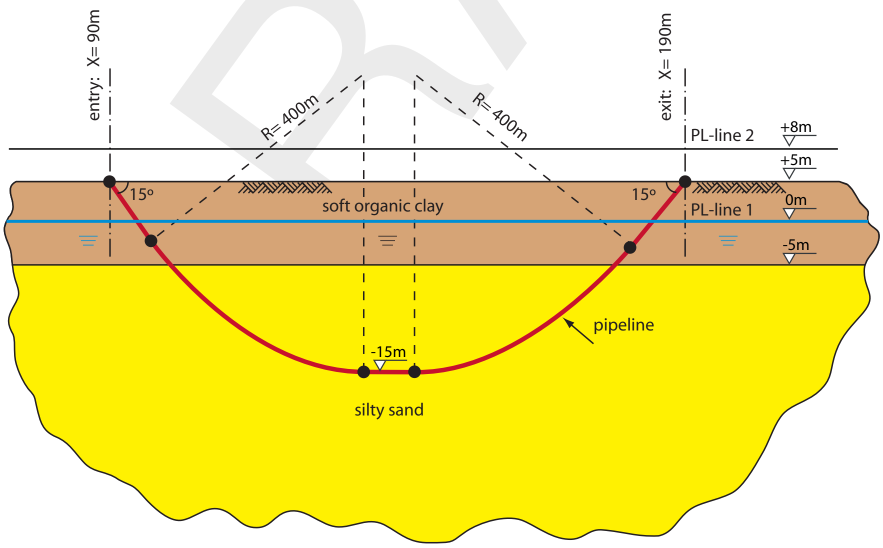


Figure 10.1: *Pipeline configuration for Tutorial 3*

Table 10.1: *Layer properties (Tutorial 3)*

		Coarse sand	Soft organic clay
Dry unit weight	[kN/m^3]	18	13
Wet unit weight	[kN/m^3]	20	13
Cohesion	[kN/m^2]	0	2
Angle of internal friction	[°]	35	18
Undrained strength top	[kN/m^2]	0	10
Undrained strength bottom	[kN/m^2]	0	30
E modulus top	[kN/m^2]	15000	500
E modulus bottom	[kN/m^2]	25000	1000
Poisson's ratio	[-]	0.35	0.45

During drilling a borehole is protected from collapsing by filling it with drilling fluid. However, arching in the surrounding soil contributes to the stability of the borehole. As a result, arching also reduces the total amount of soil load acting on the installed pipe.

For an ideal granular stratum, Terzaghi's derivation has up until now been considered to be appropriate for the situation where arching occurs and is accordingly incorporated in Dutch pipeline standard NEN 3650 series. However, for cohesive soil layers consolidation may occur over a period of time and this will result in a reduction of the arching effect, thereby increasing the vertical load on the installed pipe. The latter process is added to the Dutch pipeline standard.

For the development of arching a certain depth diameter ratio is required (Figure 10.2). At shallow depths near the exit and entry point, the soil cover is not sufficient for turning off the soil load above the borehole to the soil layers next to the borehole.

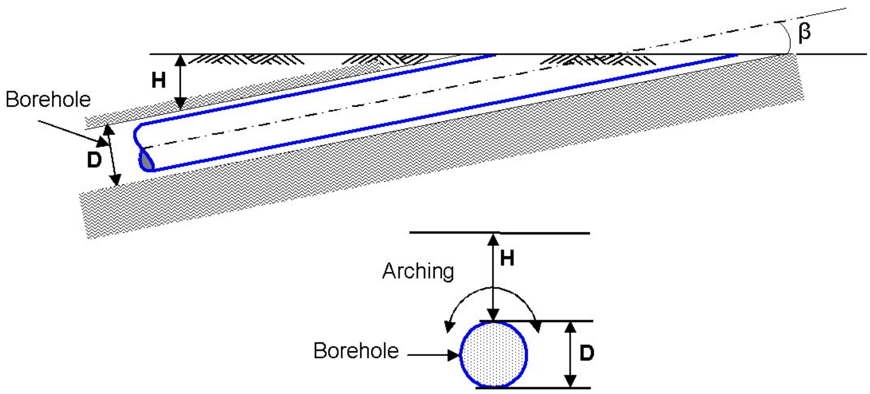


Figure 10.2: *Arching around the borehole*

During the pilot drilling the highest drilling fluid pressures occur. The risk on a blow out to the surface or the formation of cracks around the borehole often exists. This risk is related to the strength of the soil layers around the borehole. The strength of soil layers is dependent on the drained or undrained behavior of soil layers during application the drilling fluid pressure on the bore hole wall. Depending on the permeability of the soil layer, the soil will behave drained or undrained. The coarser granular soils are usually well permeable so that the excess water pressure due to the drilling fluid pressures will dissipate easily. The strength of the soil which exhibits this drained behavior can be calculated using the drained (effective) strength

parameters. In case of undrained behavior, which usually occurs in very fine grained cohesive soils, the strength of the soil should be calculated using the undrained strength parameters.

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select *Tutorial-2c* and click the *Open* button to open the file.
3. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-3>.
4. Click the *Save* button to save the file for Tutorial 3.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 3 for D-GEO PIPELINE > and <Influence of soil behavior> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

10.2 Geometry of the longitudinal cross section

This tutorial considers a layered soil sequence. The typical Dutch soil sequence of a soft organic clay layer on top of a coarse sand layer will be considered. The organic clay layer is compressible and exhibits a low permeability, while the sand layer is assumed incompressible and exhibits a high permeability. The new soil layers should be specified in the geometry window.

8. In the *View Input* window, switch to the *Geometry* tab to edit the existing soil layer sequence
9. Click the *Add single line* icon from the *Edit* sub-window to draw an additional top line of a soil and position the straight line at Z = -5 m.
10. Click the *Automatic regeneration of geometry on/off* icon to regenerate the geometry.
11. Click the *Add pl-line(s)* icon from the *Edit* sub-window and position the level of the artesian groundwater at coordinate Z = 8 m. The blue dashed line, which appears in the longitudinal cross section, represents the second groundwater line (PL line). The second groundwater line is used to specify the water pressure distribution in the sand aquifer.

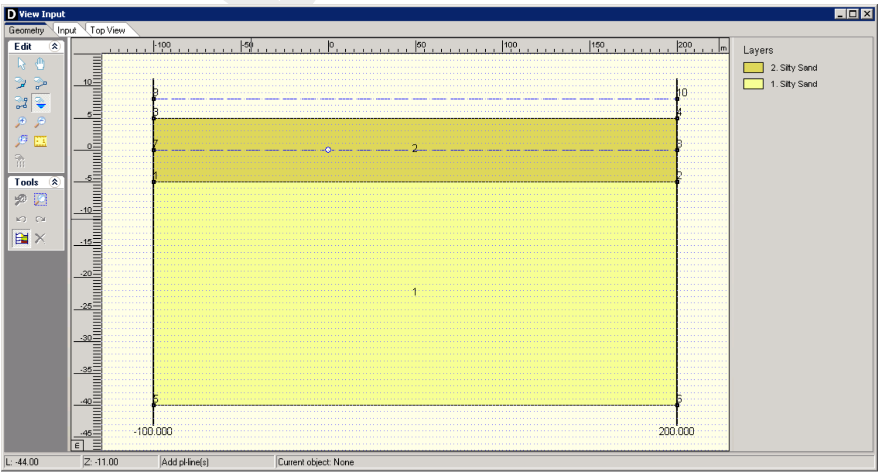


Figure 10.3: *View Input window, Geometry tab*

10.3 Soil layer properties

The properties of the soil layers in the layered soil sequence should now be specified.

12. Click *Soil* and select *Materials* on the menu bar to enter the soil data.

13. Add a new material by choosing the *Add* button Add below the materials list on the left side of the window. Enter the soil material <Coarse Sand>.
14. Enter the soil data as given in Table 10.1.
15. Add a new material by choosing the *Add* button Add below the materials list on the left side of the window. Enter the soil material <Soft Organic Clay>.
16. Enter the soil data given in Table 10.1.
17. Finish the input of soil data by clicking *OK*.

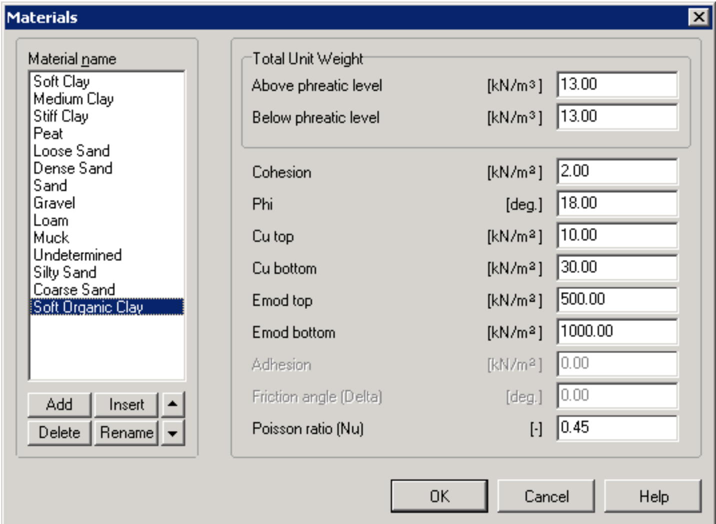


Figure 10.4: *Materials window*

10.4 Finishing the geometry of the longitudinal cross section

The defined soil properties and the groundwater levels have to be assigned to the drawn geometry of the longitudinal cross section. The assignments can be carried out in the *Geometry* menu.

18. Click *Geometry* and select *Phreatic Line* on the menu bar to open the *Phreatic Line* window (Figure 10.5) and select PL-line <1> as phreatic line for calculation of the groundwater pressures.
19. Click *OK*.

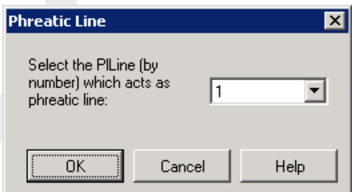


Figure 10.5: *Phreatic Line window*

20. Click *Geometry* and select *Layers* on the menu bar to open the *Layers* window. Select the *Materials* tab (Figure 10.6) to assign the soil properties to the soil layers in the longitudinal cross section.

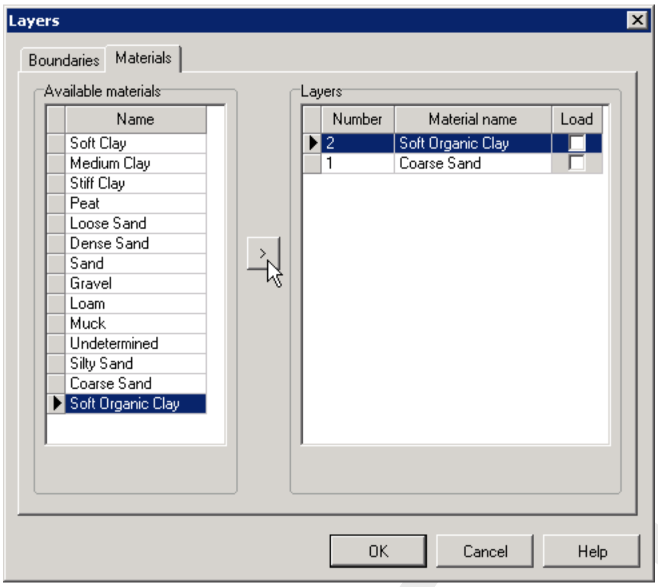


Figure 10.6: *Layers window, Materials tab*

21. Assign the properties of the defined layer *Coarse Sand* to layer *Number 1* in the longitudinal cross section. The available soil layers with defined properties are shown in left column of the materials window. The layers in the longitudinal cross section are shown in the right column of the materials window. The defined properties are assigned to layer *Number 1* by clicking the *Assign* icon in between the left and the right columns.
22. Assign the properties of the defined layer *Soft Organic Clay* to layer number 2 in the longitudinal cross section. The defined properties of *Soft Organic Clay* are assigned to layer *Number 2* by clicking the *Assign* icon in between the left and the right column.
23. Click on the *OK* button to quit the window and return to the *Geometry* tab of the *View Input* window to look at the change of layers name in the legend (Figure 10.7).

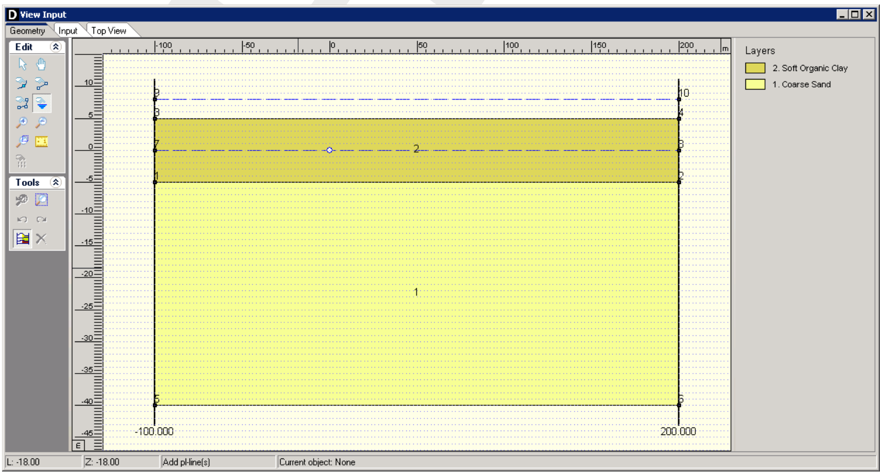


Figure 10.7: *View Input window, Geometry tab*

24. Click *Geometry* and select *Pl-lines per Layers* on the menu bar to open the *PL-lines per Layers* window to assign the defined PL–lines to the soil layers in the longitudinal cross section. Those information's are used for the calculation of the groundwater pressure distribution.
25. The groundwater pressure at the top of the *Soft Organic Clay* layer should be calculated based on the hydraulic head of PL–line 1, the phreatic line (Figure 10.1). Since the *Coarse*

Sand layer is an aquifer with an enhanced artesian groundwater pressure, the groundwater pressure at the bottom of the clay layer should be calculated based on the hydraulic head of PL–line 2. Of course the water pressure at the top and at the bottom of the coarse sand layer should be calculated based on the hydraulic head of PL–line 2. This will result in the *Pl-lines per layer* window shown in Figure 10.8.

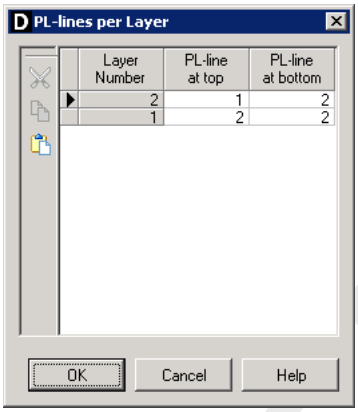


Figure 10.8: *PL-lines per Layer window*

26. Click *OK* to confirm.
27. The geometry can be tested by clicking *Geometry* on the menu bar and selecting *Check Geometry*. If the geometry is entered properly, the message *Geometry has been tested and is OK* appears.
28. Click *OK* to close this window.

10.5 Soil behavior

Strength of soil layers is dependent on the drained or undrained behavior of soil layers during application the drilling fluid pressure. Depending on the permeability of the soil layer, the soil will behave drained or undrained. The *Coarse Sand* layer is well permeable so that the excess water pressure due to the drilling fluid pressures will dissipate easily. The strength of this soil layer can be calculated using the drained (effective) strength parameters effective cohesion (c) and angle of internal friction (φ). In case of undrained behavior in the impermeable *Soft Organic Clay* layer, the strength of the soil can be calculated using the undrained strength parameter undrained cohesion (c_u).

The soil load on the pipeline after finishing the installation is dependent on the soil pipeline interaction, which is in turn largely dependent on the soil behavior. In D-GEO PIPELINE it is assumed that the pipeline remains fixed at the specified location and that there's no settlement of the soil layers below the pipeline. This assumption allows D-GEO PIPELINE to perform a relative simple pipe stress analysis based on a reduced soil load due to arching. As described in section 10.2, arching develops completely in incompressible soil layers, while in compressible layers the reduced soil load on the pipeline is higher due to compression of the soil next to the pipeline.

29. Click *GeoObjects* and select *Boundaries Selection* on the menu bar to open the *Boundaries Selection* window for specification of the soil behavior.
30. Choose the boundary between the undrained and drained layer on top of layer number $<1>$ (Figure 10.9). This choice results in drained behavior of layer number 1.
31. Choose the boundary between the compressible and incompressible layer on top of layer number $<1>$. This choice results in full development of arching in layer number 1 while in layer number 2 arching is not fully developed.

32. Click *OK* to close this window.

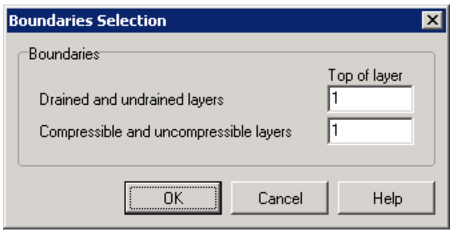


Figure 10.9: *Boundaries Selection window*

10.6 Calculated reduced soil load for pipe stress analysis

The layered soil sequence results in a different reduced neutral soil load at different depths. Due to the compressible top layer, the reduced neutral soil load increases considerable with increasing depth (Figure 10.10). In the sand layer, the reduced neutral soil load reduces due to the full development of arching.

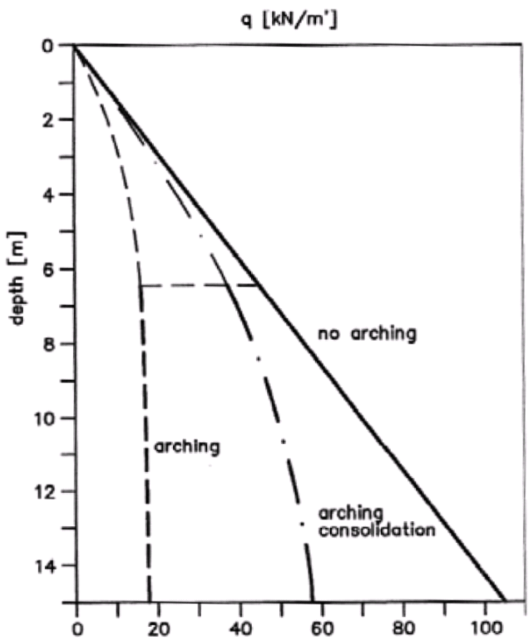
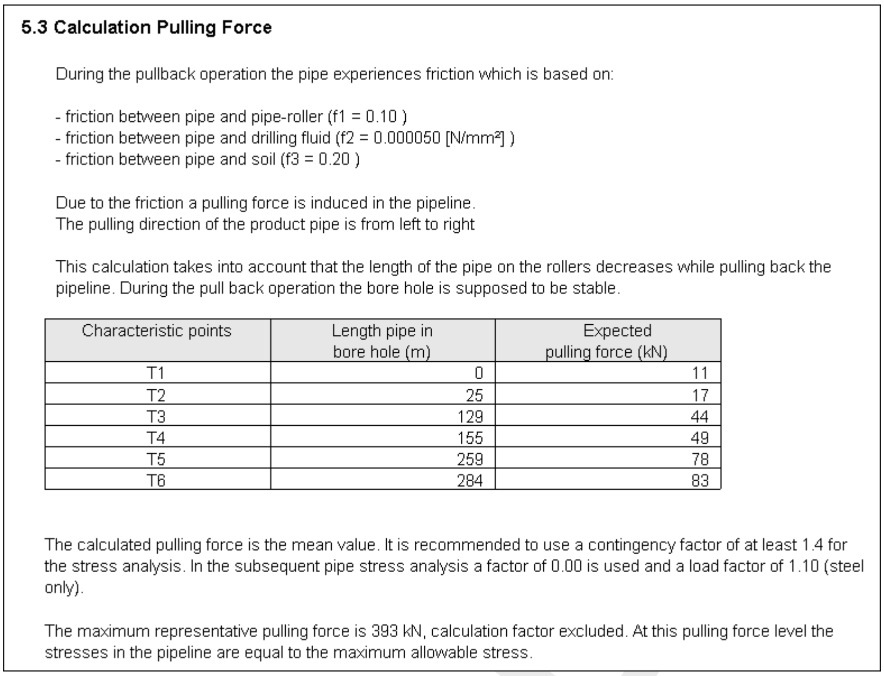


Figure 10.10: *The effect of arching with increasing depth (Meijers and De Kock, 1995)*

33. To start the calculations, click *Calculation* and select *Start* on the menu bar or press the function key F9.
34. Click *Results* and select *Report* on the menu bar to look at the results of the pipe stress analysis.



5.3 Calculation Pulling Force

During the pullback operation the pipe experiences friction which is based on:

- friction between pipe and pipe-roller (f1 = 0.10)
- friction between pipe and drilling fluid (f2 = 0.000050 [N/mm²])
- friction between pipe and soil (f3 = 0.20)

Due to the friction a pulling force is induced in the pipeline.
The pulling direction of the product pipe is from left to right

This calculation takes into account that the length of the pipe on the rollers decreases while pulling back the pipeline. During the pull back operation the bore hole is supposed to be stable.

Characteristic points	Length pipe in bore hole (m)	Expected pulling force (kN)
T1	0	11
T2	25	17
T3	129	44
T4	155	49
T5	259	78
T6	284	83

The calculated pulling force is the mean value. It is recommended to use a contingency factor of at least 1.4 for the stress analysis. In the subsequent pipe stress analysis a factor of 0.00 is used and a load factor of 1.10 (steel only).

The maximum representative pulling force is 393 kN, calculation factor excluded. At this pulling force level the stresses in the pipeline are equal to the maximum allowable stress.

Figure 10.11: *Report window, Calculation Pulling Force*

10.7 Calculated drilling fluid pressures

The existence of soft organic soil layer with low strength and high deformability characteristics influences the results of the maximal allowable drilling fluid pressures.

35. Click *Results* and select *Drilling Fluid Pressure Plots* on the menu bar to open the *Drilling Fluid Pressure* window (Figure 10.12) and to look at the results of the drilling fluid pressure calculations for the pilot drilling.

The graph shows the maximum allowable pressures (upper limit related to soil cover and lower limit related to deformation of the borehole) and the minimal required drilling fluid pressure for transportation of the cuttings. Notice that for the pilot stage the minimal allowable drilling fluid pressure is higher than the maximal allowable drilling fluid pressure at the last part of the upward bend of the drilling. This means that the risk of a blow out is present, so that measures are required.

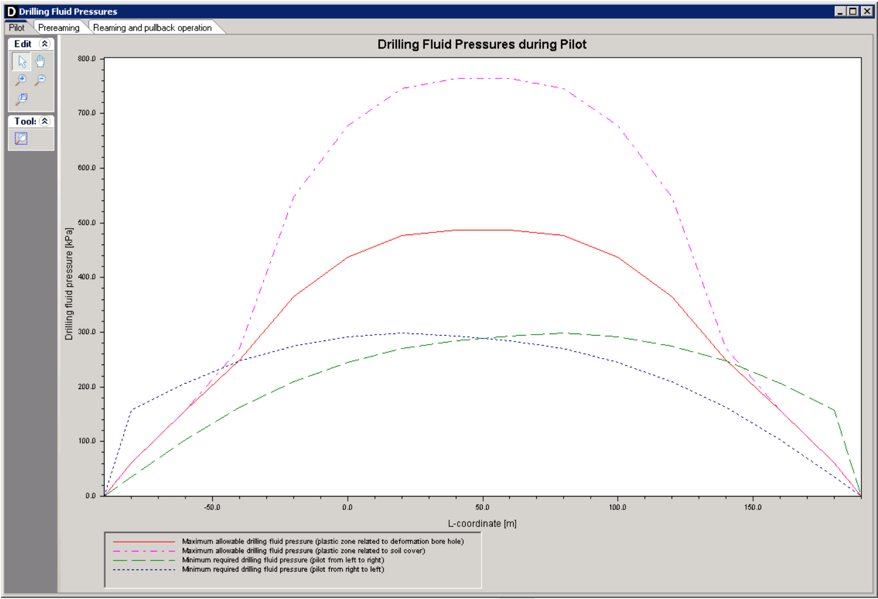


Figure 10.12: *Drilling Fluid Pressures window*

36. Click on the tabs *Prereaming* and *Reaming and pullback operation* to look at the results of the other drilling stages.
37. Close the window to return to the main menu.

10.8 Drilling fluid pressure and groundwater pressure

During the stages of horizontal directional drilling the borehole is filled with drilling fluid. The drilling fluid has a certain unit weight, which is largely dependent on the initial unit weight of the drilling fluid and the amount of cut soil material in the drilling fluid. If the borehole is located in soil layers with an artesian water pressure (aquifers), the risk of leakage of groundwater through the borehole to the surface exists. The leakage of groundwater will result in flow of water through the borehole, which in turn will lead to borehole instability (when the drilling fluid is flown out of the borehole located in coarser granular layers). This risk is automatically assessed when a D-GEO PIPELINE calculation is performed.

38. Click *Results* and select *Report* on the menu bar to watch the results of leakage assessment in paragraph 3.2 (equilibrium between drilling fluid pressure and pore pressure). Notice that the artesian water pressure is higher than the drilling fluid pressure so that measures against leakage are required (Figure 10.13).

3.2 Equilibrium between Drilling Fluid Pressure and Pore Pressure

Vertical nr.	Static column pressure			
	Drilling fluid [kN/m²]	Water [kN/m²]	Safety [-]	Result
1	30	0	-	sufficient
2	89	78	1.14	sufficient
3	138	155	0.89	not sufficient
4	176	189	0.93	not sufficient
5	203	213	0.95	not sufficient
6	218	226	0.96	not sufficient
7	222	230	0.97	not sufficient
8	222	230	0.97	not sufficient
9	218	226	0.96	not sufficient
10	203	213	0.95	not sufficient
11	176	189	0.93	not sufficient
12	138	155	0.89	not sufficient
13	89	78	1.14	sufficient
14	30	0	-	sufficient

The static drilling fluid pressure is calculated and can be compared with the calculated groundwater pressure. The quotient of the drilling fluid pressure and the groundwater pressure yields the safey factor, which should be higher than the requested factor of safety of 1.10.

Figure 10.13: *Report window, Equilibrium between drilling fluid pressure and pore pressure*

10.9 Conclusion

In this tutorial, a layered soil sequence has been modeled and the drilling fluid pressures have been calculated. Using the table called *Equilibrium between drilling fluid pressure and pore pressure* in the D-GEO PIPELINE report, it can be concluded if the drilling fluid pressures are or are not sufficient.

11 Tutorial 4: Exporting soil mechanical data for an extended stress analysis

This exercise considers the installation of a polyethylene pipeline by using the horizontal directional drilling technique. The exercise focuses on the calculation of soil mechanical parameters for an extended pipe stress analysis. A settlement calculation forms also part of the exercise.

The objectives of this tutorial are:

- ◇ To calculate the soil mechanical parameters for an extended pipe stress analysis;
- ◇ To perform a settlement calculation;
- ◇ To export the soil mechanical parameters.

The following module is needed:

- ◇ D-GEO PIPELINE Standard module (HDD)
- ◇ License for D-SETTLEMENT (formerly known as MSettle)

This tutorial is presented in the file Tutorial-4.dri.

11.1 Introduction to the case

In D-GEO PIPELINE it is assumed that the pipeline remains fixed at the specified location and that there's no settlement of the soil layers below the pipeline. No temperature effects are taken into account in D-GEO PIPELINE. Therefore a relative simple pipe stress analysis can be performed.

In case compressible soil layers are present below the pipeline and an additional load is carried out on theses compressible soil layers, settlement can be expected. If settlement of the layers below the pipeline occurs in most cases, an extended pipe stress analysis is required. The extended pipe stress analysis can not be performed using D-GEO PIPELINE, but should be carried out using other software. For instance SCIA pipeline can be used for such an analysis.

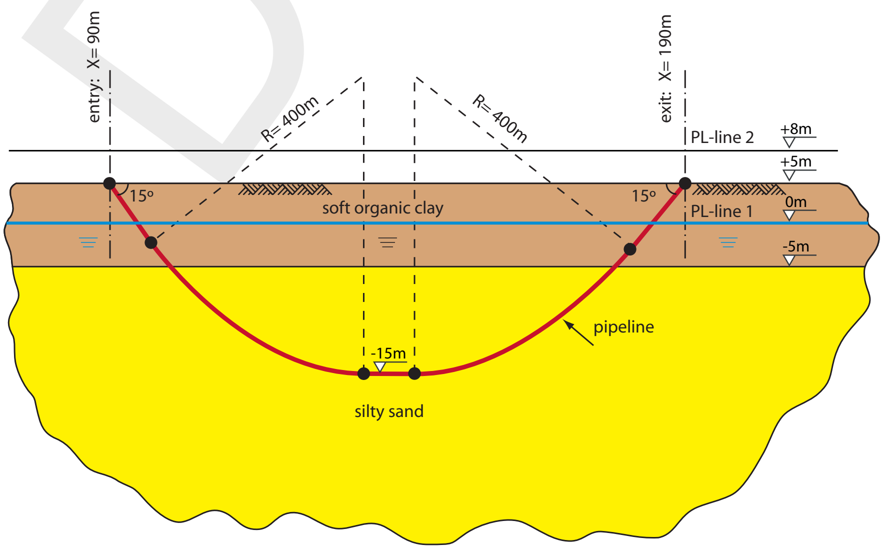


Figure 11.1: *Pipeline configuration for Tutorial 4*

Vertical displacement of soil below and around the pipeline that occurs after installation is an important factor in assessing the stresses in the pipeline. Settlement may be entered manually if the vertical settlements results are available. For more accurate results, D-GEO PIPELINE can use the D-SETTLEMENT computer program (formerly known as MSettle) without additional input. Settlement deals with soil compaction due to imposed loading. In D-GEO PIPELINE the loading consists of an extra layer as created in the geometry. The calculation of the settlement is performed externally by D-SETTLEMENT, the settlement calculation program of the Deltares Systems tools. Details on the calculation of settlement are beyond the scope of this manual, a thorough description can be found in the user manual of D-SETTLEMENT (Deltares).

Table 11.1: *Settlement parameters (acc. Koppejan) of the soil layers (Tutorial 4)*

	Coarse sand	**Soft organic clay**
Over-consolidation ratio	1.3	1.3
Primary compression coefficient below Pc	10^9	40
Primary compression coefficient above Pc	10^9	10
Secondary compression coefficient below Pc	10^9	160
Secondary compression coefficient above Pc	10^9	35

This tutorial is based on continuation of the file used in Tutorial 3 (chapter 10).

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select the file *Tutorial-3* and click the *Open* button.
3. Click*File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-4>.
4. Click the *Save* button to save the file for Tutorial 4.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 4 for D-GEO PIPELINE > and <Exporting soil mechanical data> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

11.2 Settlement model

Settlement calculations can be performed using the in the Netherlands often used Koppejan model or the more recent developed Isotache model which is based on Terzaghi's settlement model.

8. Click *Project* and select *Model* on the menu bar to open the *Model* window (Figure 11.2).
9. Select the *Horizontal directional drilling* method and mark the *Use settlement* check-box.
10. Select the *Koppejan* model.
11. Click *OK* to confirm the choice.

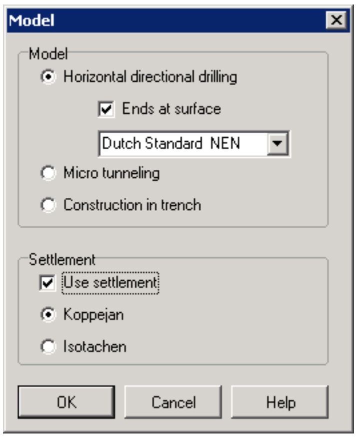


Figure 11.2: *Model window*

11.3 Geometry of the longitudinal cross section

This tutorial considers a layered soil sequence described in Tutorial 3 (chapter 10). In the longitudinal cross section, a load (soil mass) has to be defined.

12. Switch to the *Geometry* tab in the *View Input* window to edit the existing soil layer sequence.
13. Select the *Add polyline* icon from the *Edit* sub-window to draw an additional layer (soil mass) on top of the existing soil layers with coordinates given in Table 11.2.

Table 11.2: *Coordinates of the top of the soil mass*

X coordinate [m]	Z coordinate [m]
-75	5
-60	10
30	10
45	5

14. Quit editing by clicking the right mouse button.
15. To check or modify the added points, select a point by clicking the left mouse button. The point will become a red square.
16. Click the right-hand mouse button and select *Properties*. In the window displayed (Figure 11.3), the co-ordinates can be checked and modified if needed.

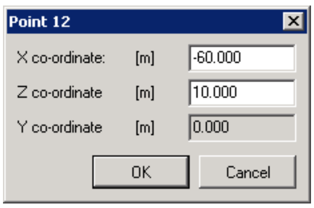


Figure 11.3: *Point window*

17. Select the *Automatic regeneration of geometry on/off* icon from the *Tools* sub-window so that the geometry as shown in Figure 11.4 appears. If the *Automatic regeneration of geometry* icon already is selected, click on the *Edit* icon to regenerate the geometry. Notice that the soil mass is located on the left side above the section where the pipeline is located in the *Soft Organic Clay* layer.

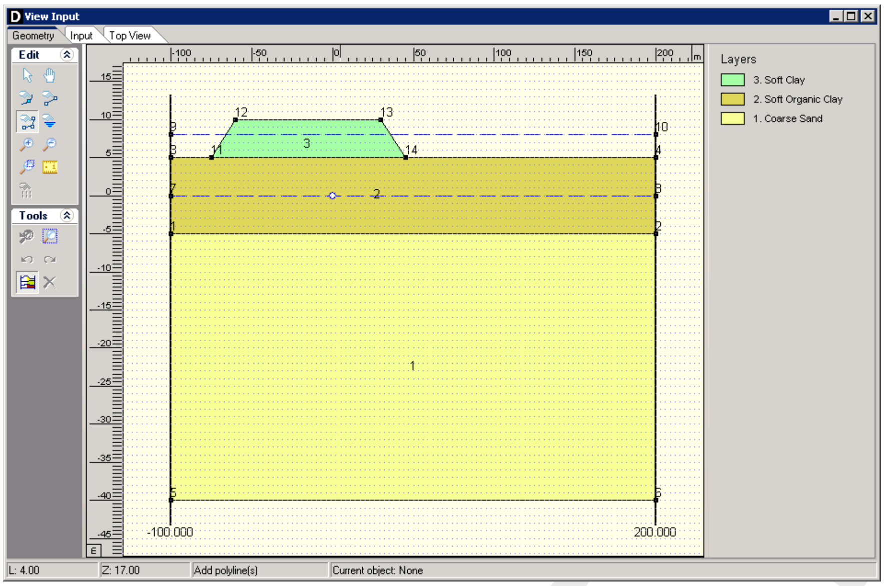


Figure 11.4: *View Input window, Geometry tab*

11.4 Soil layer properties

The settlement properties of the soil layers in the layered soil sequence should now be specified. The properties of the soil mass should be entered too.

18. Click *Soil* and select *Materials* on the menu bar to open the *Materials* window.
19. Select the soil name *Silty Sand* in the left column of the *Materials* window and enter the properties given in Figure 11.5.
20. Select the soil name *Coarse Sand* and enter the *Settlement Koppejan* data given in Table 11.1.
21. Select the soil name *Soft Organic Clay* and enter the *Settlement Koppejan* data given in Table 11.1.
22. Finish the input of soil data by clicking *OK*.

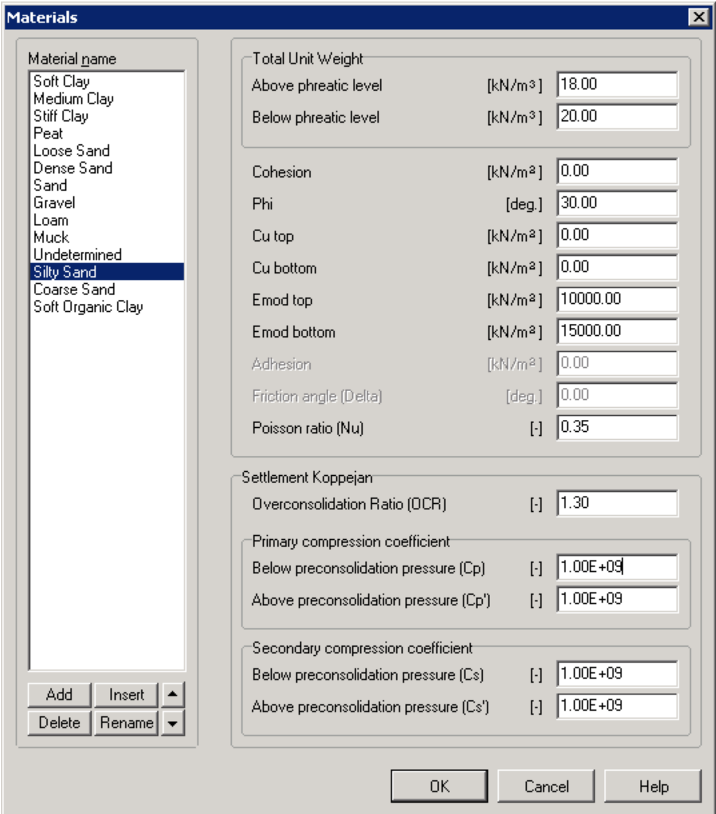


Figure 11.5: *Materials window*

11.5 Finishing the geometry of the longitudinal cross section

The defined soil properties have to be assigned to the drawn geometry of the longitudinal cross section (groundwater levels are assigned already). The assignments can be carried out by clicking geometry and choosing the subsequent described options on the menu bar.

23. Click *Geometry* and select *Layers* on the menu bar to open the *Layers* window to assign the soil properties to the soil layers in the longitudinal cross section.
24. Click on the tab *Materials*.
25. Assign the soil properties given in Figure 11.6.
26. Click *OK* to confirm the assignments.

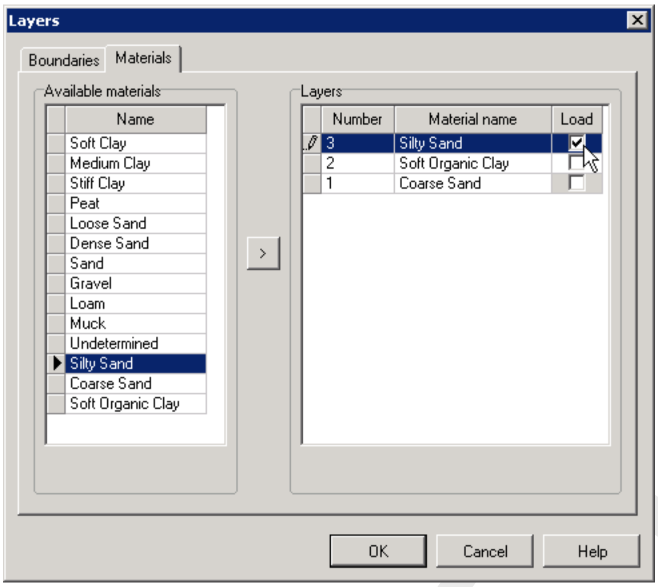


Figure 11.6: *Layers window, Materials tab*

11.6 Calculated soil mechanical parameters in export file

The calculation of the settlement of the soil layers below the pipeline is performed externally by D-SETTLEMENT (formerly known as MSettle), the settlement calculation program of the Deltares Systems tools. Therefore, the directory where the program is installed must be given:

27. Click *Tools* on the menu bar and select *Program Options* to open the *Program Options* window. Then select the *Locations* tab (Figure 11.7).
28. If needed, change the directory where the *Settlement program* is installed by clicking the *Browse* button.
29. Click *OK* to confirm.

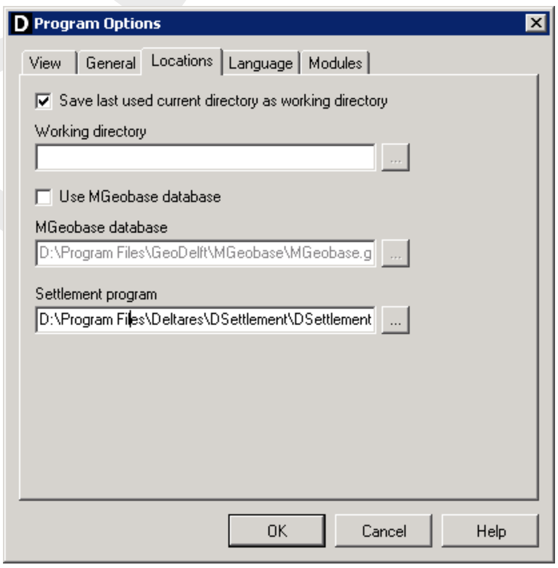


Figure 11.7: *Program Options window, Locations tab*

The other soil mechanical parameters are calculated automatically in D-GEO PIPELINE.

30. To start the calculations click *Calculation* and select *Start* on the menu bar to or press the function key F9. Ignore the message of Cu values of 0 above the drained undrained boundary.
31. Click *Results* and select *Report* on the menu bar to look at the results of the settlement calculation in paragraph 3.1 (Figure 11.8) and the calculation of the soil mechanical parameters in paragraph 4.1.

4 Deformations

4.1 Settlements of soil layers below the Pipeline

Vertical nr. [-]	Settlement [mm]	Additional settlement [mm]	dv [mm]
1	58	0	58
2	735	0	735
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0

Figure 11.8: *Report window, Settlements along pipeline*

32. Click *File* and select *Export Results as csv. . .* on the menu bar to create an export file with the soil mechanical parameters.
33. Click on the *Save* button. The export file is saved on the same directory as Tutorial 4 and can be opened using the Excel program for example (see Figure 11.9).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	
1																						
2																						
3																						
4																						
5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
6	Header	Header	Header	Header	Bundle	Bundle	Bundle	Bundle	Bundle	Bundle	Bundle	Pipe	Pipe	Pipe	Pipe	Section	Section	Section	Section	Section	Section	Se
7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Axial	Axial	Axial	Axial	Horizontal	Horizontal	H
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	Company	Software	Date	Time	P1(x)	P1(y)	P1(z)	P2(x)	P2(y)	P2(z)	Length Pip	Pipe nr	Diameter T	Thickness T	Material Tu	Section nr	x	y	z	From	Curved	D
10	[-]	[-]	[yyyy/mm/c	[hh:mm:ss]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	-	[mm]	[mm]	-	-	[m]	[m]	[m]	[m]	[boolean]	[n
11		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	1	-80	0	2.32	10.35	ToDoBool	
12		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	2	-60	0	-2.99	31.04	ToDoBool	
13		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	3	-40	0	-7.46	51.54	ToDoBool	
14		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	4	-20	0	-10.87	71.83	ToDoBool	
15		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	5	0	0	-13.26	91.98	ToDoBool	
16		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	6	20	0	-14.63	112.03	ToDoBool	
17		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	7	40	0	-15	132.03	ToDoBool	
18		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	8	60	0	-15	152.03	ToDoBool	
19		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	9	80	0	-14.63	172.04	ToDoBool	
20		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	10	100	0	-13.26	192.09	ToDoBool	
21		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	11	120	0	-10.87	212.23	ToDoBool	
22		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	12	140	0	-7.46	232.52	ToDoBool	
23		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	13	160	0	-2.99	253.02	ToDoBool	
24		D-Geo Pipe	22-7-2013	23:06:10	-80	0	2.32	180	0	2.32	284.06	1	400	36.4	Polyethene	14	180	0	2.32	273.71	ToDoBool	

Figure 11.9: *Content of the export file for Tutorial 4*

The export file contains:

◇ Horizontal soil data
◇ Vertical soil data
◇ Soil data for friction
◇ Data of pipeline

For more information, refer to section 3.1.2.

11.7 Conclusion

A pipe stress and settlement analysis has been performed for a polyethylene pipe in a layered soil. The inputs and results of this calculation have been exported in a csv file in order to perform an extended stress analysis using an other program such as SCIA pipeline.

12 Tutorial 5: Drilling with a horizontal bending radius

This fifth exercise considers installation of a polyethylene pipeline by using the technique horizontal directional drilling. The exercise focuses on a horizontal bending radius in the design of the drilling line.

The objectives of this tutorial are:

◇ To schematize a horizontal bending;
◇ To calculate pulling forces in the horizontal bending;
◇ To perform a pipe stress analysis for the design with a horizontal bending radius.

The following module is needed:

◇ D-GEO PIPELINE Standard module (HDD)

This tutorial is presented in the file Tutorial-5.dri.

12.1 Introduction to the case

A horizontal bending radius in the design drilling line is observed more frequent. Often the horizontal bend is part of one of the vertical bending radii. In case the horizontal bending radius coincides with part of a vertical bending radius, a combined 3-dimensional bending radius is formed. For the design of the horizontal directional drilling line, the pull back force and the strength calculation it is necessary to determine the value of the 3 dimensional bending radius.

The value of the three dimensional bending radius can be calculated as follows:

$$R_{\text{combi}} = \sqrt{\frac{R_{\text{h}}^2 \times R_{\text{v}}^2}{R_{\text{h}}^2 + R_{\text{v}}^2}} \tag{12.1}$$

where:

R_{combi}	is the combined bending radius, in m;
R_{h}	is the horizontal bending radius, in m;
R_{v}	is the vertical bending radius, in m.

The combined bending radius is used to calculate the pulling force during the pull back operation and is used in the pipe stress analysis in D-GEO PIPELINE.

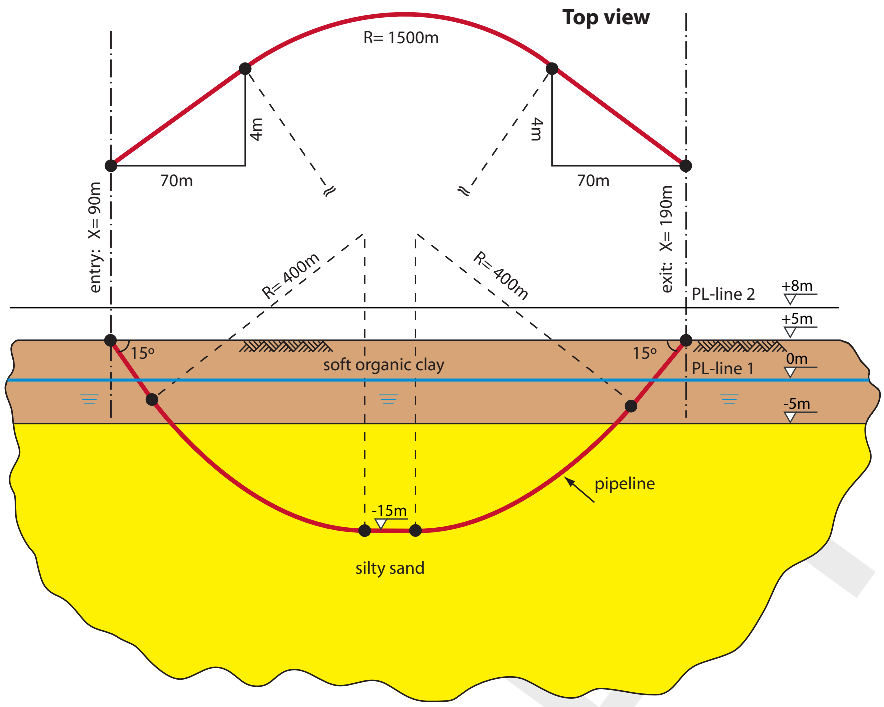


Figure 12.1: *Pipeline configuration of Tutorial 5*

This tutorial is based on continuation of the file used in Tutorial 3 (chapter 10).

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select *Tutorial-3* and click the *Open* button to open the file.
3. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-5>.
4. Click the *Save* button to save the file for Tutorial 5.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 5 for D-GEO PIPELINE > and <Drilling with a horizontal bending radius> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

12.2 Pipeline Configuration

The horizontal bend must be specified in the pipeline configuration window.

8. Click *Pipe* and select *Pipeline Configuration* on the menu bar to open the *Pipeline Configuration* window.

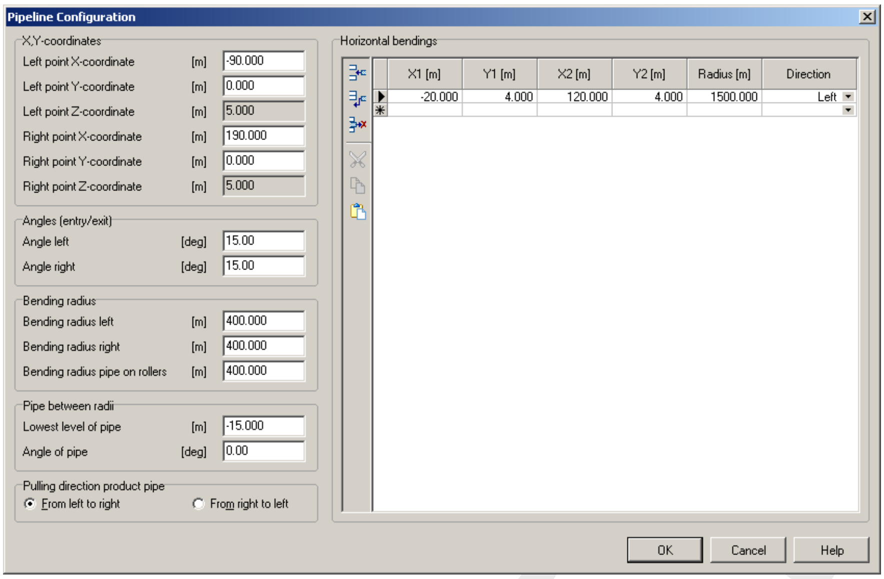


Figure 12.2: *Pipeline Configuration window*

9. Enter the values given in Figure 12.1.
10. Click *OK* to confirm.
11. Look at the entered horizontal bending on the *Top View* tab of the *View Input* window (Figure 12.3).
12. Look at the longitudinal cross section on the *Input* tab of the *View Input* window and notice the elongation of the longitudinal cross section. Therefore it is recommended to check, in case of projects with changing 3D pipeline configurations, if the soil layer sequence in the longitudinal cross section is still reliable (according to the soil investigation data).

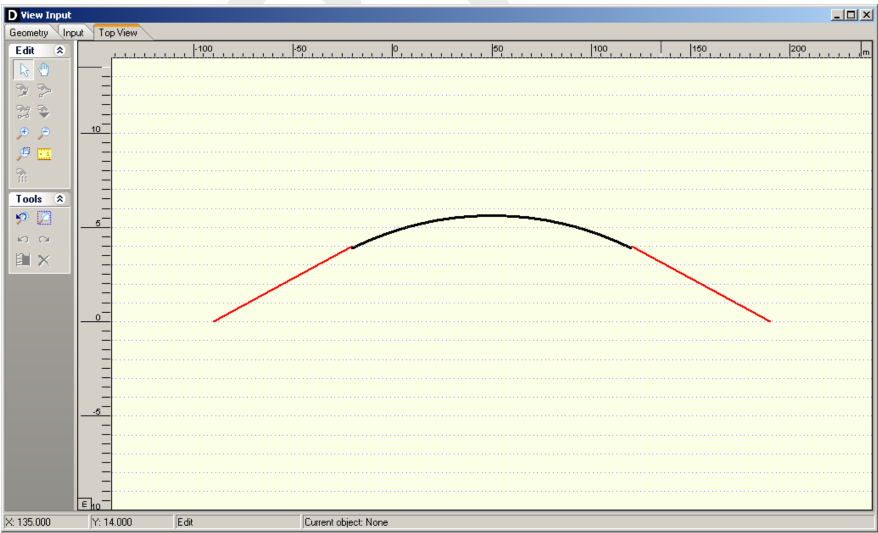


Figure 12.3: *View Input window, Top View tab*

Note: The horizontal bending is indicated with a black bold line in the longitudinal cross section (Figure 12.4).

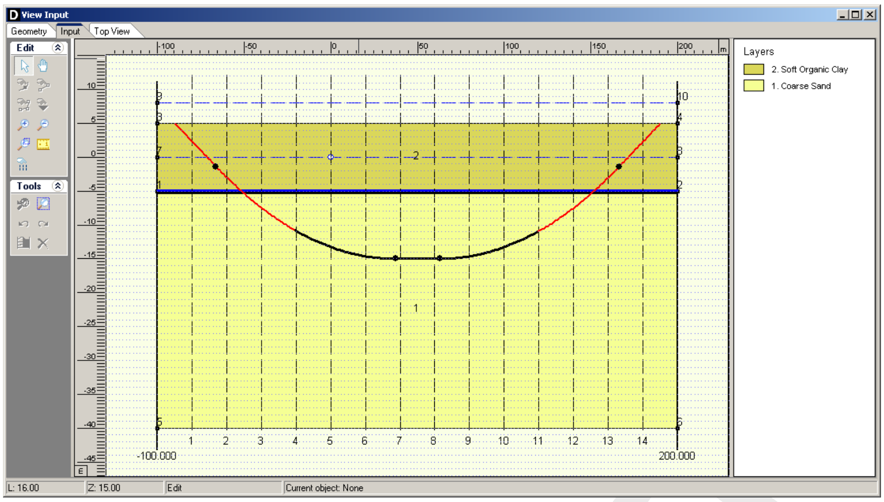


Figure 12.4: *View Input window, Input tab*

12.3 Calculation of the pulling force and pipe stress analysis

The results of the pulling force calculation are shown in the D-GEO PIPELINE report which is created automatically after finishing the calculations.

13. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.
14. Click *Results* and select *Report* n the menu bar to look at the results of the pulling force calculations. The results can be found on paragraph 5.3 (Figure 12.5).

Note the increase in pulling force due the horizontal bending radius compare to the case without bending (see results of Tutorial 3 in Figure 10.11).

5.3 Calculation Pulling Force

During the pullback operation the pipe experiences friction which is based on:

- friction between pipe and pipe-roller (f1 = 0.10)
- friction between pipe and drilling fluid (f2 = 0.000050 [N/mm²])
- friction between pipe and soil (f3 = 0.20)

Due to the friction a pulling force is induced in the pipeline.
The pulling direction of the product pipe is from left to right

This calculation takes into account that the length of the pipe on the rollers decreases while pulling back the pipeline. During the pull back operation the bore hole is supposed to be stable.

Characteristic points	Length pipe in bore hole (m)	Expected pulling force (kN)
T1	0	11
T2	25	17
T3	129	44
T4	155	50
T5	260	79
T6	284	85

The calculated pulling force is the mean value. It is recommended to use a contingency factor of at least 1.4 for the stress analysis. In the subsequent pipe stress analysis a factor of 0.00 is used and a load factor of 1.10 (steel only).

The maximum representative pulling force is 392 kN, calculation factor excluded. At this pulling force level the stresses in the pipeline are equal to the maximum allowable stress.

Figure 12.5: *Report window, Calculation Pulling Force*

In paragraph 5.1 (Figure 12.6), the data for the pipe stress analysis is given. The value of the

minimal bending radius is equal to R_{min} = 386 m.

5.1 General Data

Pipeline diameter	:	Do = 400.00 mm
Wall thickness	:	t = 36.4 mm
Unit weight pipeline material	:	gamma_s = 9.54 kN/m³
Unit weight drilling fluid pullback operation	:	gamma_b = 11.10 kN/m³
Minimum bending radius	:	R = 386 m
Friction coefficient pipe/rollers	:	f1 = 0.10
Friction between pipe and drilling fluid	:	f2 = 0.000050 N/mm²
Friction coefficient pipe / soil	:	f3 = 0.20
Maximal modulus of subgrade reaction	:	kv, max = 62287 kN/m³

Figure 12.6: *Report window, General Data*

The minimum bending radius is used to calculate the stresses in the pipeline. In the assessment table in paragraph 6.3 of the report, the influence of a smaller bending radius is visible: higher axial and tangential stresses in both the installation stages and the operational stage after installation.

12.4 Conclusion

This tutorial models a horizontal bending in the pipeline configuration. The calculated pulling forces increase compare to the case without horizontal bending presented in Tutorial 3.

13 Tutorial 6: Installation of bundled pipelines

This sixth tutorial considers installation of a bundle consisting of five polyethylene pipelines by using the technique horizontal directional drilling. The exercise focuses on the background of the automatic bundle calculation in D-GEO PIPELINE.

The objectives of the exercise are:

- ◇ To calculate the drilling fluid pressures for the pull back operation;
- ◇ To calculate the pulling force on the bundled pipelines during the pull back operation;
- ◇ To perform an automatic pipe stress analysis for the pipelines in the bundle.

The following module is needed:

- ◇ D-GEO PIPELINE Standard module (HDD)

This tutorial is presented in the file Tutorial-6.dri.

13.1 Introduction to the case

The calculations required for the installation of bundled pipelines using the horizontal directional drilling technique are rather similar to those for the installation of a single pipeline. Differences exist in the calculations:

- ◇ For the minimal required drilling fluid pressure during the pull back operation
- ◇ For the pulling force during the pull back operation
- ◇ For the pipe stress analysis (differences in assumptions)

Ad 1) Of course the available space for the back flow of the drilling fluid is different in case of a bundled pipeline. For calculation of the minimal required drilling fluid pressure, D-GEO PIPELINE assumes flow of the drilling fluid

- ◇ through the space in between the bundle and the borehole wall
- ◇ and through the space in the bundle, in between the pipelines.

Ad 2) Important parameters for the calculation of the pulling force during the pullback operation are the total effective weight of the (filled) pipelines in the bundle and the total stiffness of the bundle which determines the soil reaction force in curved sections of the drilling line. In D-GEO PIPELINE the pulling force is calculated for an equivalent pipeline with the weight and stiffness parameters of the bundled pipelines.

$$EI_{\text{eq}} = \sum_{n}^{i=1} E_{\text{i}} I_{\text{i}} \tag{13.1}$$

$$G_{\text{tot}} = \sum_{n}^{i=1} \left(\frac{\pi}{4} D_{\text{o;i}}^2 - \frac{\pi}{4} \left(D_{\text{0;i}} - 2d_{\text{n;i}} \right)^2 \right) \times \gamma_{\text{i}} \tag{13.2}$$

where:

n	is the total number of pipelines in the bundle;
$D_{\text{o;i}}$	is the outer diameter of pipeline i, in m;
$d_{\text{n;i}}$	is the wall thickness of pipeline i, in m;
γ_{i}	is the unit weight of pipeline i, in kN/m^3;
E_{i}	is the Young's modulus of pipeline i, in kN/m^2;

I_i is the moment of inertia of pipeline i, in m^4;
I_eq is the moment of inertia of the bundle, in m^4.

The calculated pulling force is acting on all the pipelines in the bundle. The magnitude of the pulling force of a pipeline in the bundle is derived by dividing the total pulling force over the cross section area of the wall of the pipelines with equal stiffness.

In case the stiffness of the pipeline materials is significantly different (for example a combined bundle of steel and PE pipelines), a different approach is applied. In addition to the previous described dividing procedure, the total pulling force is assigned to the stiffer pipeline (steel pipeline).

Ad 3) The pipe stress analysis for a pipeline in the bundle is quite similar to the pipe stress analysis for a single pipeline in the bore hole. The only difference in the pipe stress analysis is the contact between the pipeline and the surrounding soil (single pipeline) and the contact between the pipeline and the adjacent pipelines (bundle). Therefore the load angle and the bedding angle should be adapted in case of a bundled pipeline. In this tutorial angle values of 30 degrees are assumed and entered manually.

Table 13.1: *Pipes properties (Tutorial 6)*

		Pipe 1	**Pipe 2**
Material quality		PE80	PE80
Young's modulus (short term)	[N/mm^2]	1000	1000
Young's modulus (long term)	[N/mm^2]	200	200
Allowable strength (short term)	[N/mm^2]	10	10
Allowable strength (long term)	[N/mm^2]	8	8
Tensile factor	[-]	0.65	0.65
Outer Diameter	[mm]	400	160
Wall thickness	[mm]	36.4	12.3
Unit weight pipe material	[kN/m^3]	9.54	9.54
Design pressure	[Bar]	4	4
Test pressure	[Bar]	5	5
Temperature variation	[°C]	5	5

This tutorial is based on continuation of the file used in Tutorial 5 (chapter 12).

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select *Tutorial-5* and click the *Open* button to open the file.
3. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-6>.
4. Click the *Save* button to save the file for Tutorial 6.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 6 for D-GEO PIPELINE > and <Installation of bundled pipelines> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

13.2 Product Pipe Material Data

The dimensions and the properties of the product pipes in the bundle should be specified.

8. Click *Pipe* and select *Product Pipe Material Data* on the menu bar to open the *Product Pipe Material Data* window for specification of the dimensions and properties of the product pipes in the bundle.
9. Change the following values for *Pipe 1* in the fields on the right side of the window (Figure 13.1).

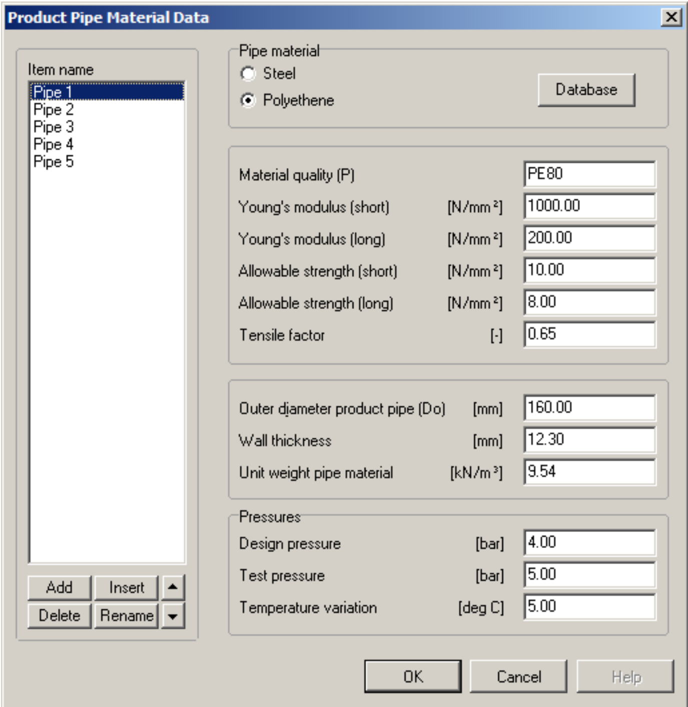


Figure 13.1: *Product Pipe Material Data window*

10. Click on the *Add* button 

on the left side of the window to declare a pipeline with the name <Pipe 2>.
11. Enter the values for Pipe 2 (Table 13.1), in the fields on the right side of the window.
12. Click on the *Add* button on the left side of the window three times to add three more pipes. Notice that the material properties of Pipe 2 are automatically copied to these pipes.
13. Use the *Rename* button on the left side of the window to rename the new pipes into <Pipe 3>, <Pipe 4> and <Pipe 5>.
14. Click on *OK* to confirm the specified product pipe material data.

The bundle now consists of five pipes:

- ◇ Pipe nr. 1: 400 mm SDR 11 PE 80
- ◇ Pipe nr. 2: 160 mm SDR 13 PE 80
- ◇ Pipe nr. 3: 160 mm SDR 13 PE 80
- ◇ Pipe nr. 4: 160 mm SDR 13 PE 80
- ◇ Pipe nr. 5: 160 mm SDR 13 PE 80

13.3 Drilling Fluid Data

The properties of the drilling fluid and the operation parameter values should be specified for the bundle.

15. Click *Pipe* and select *Drilling Fluid Data* on the menu bar to open the *Drilling Fluid Data* window for specification of properties of the drilling fluid.
16. Enter the values of Figure 13.2 for installation of the bundle. The bedding and the load angle are 30 degrees since contacts in between the pipelines are expected. These values are used in the pipe stress analysis to determine the moment coefficients. The values for the special pipe stress analysis do not have to be entered.
17. Click on the *OK* button to confirm the input of the specified value.

Note: The equivalent diameter of the bundle is calculated automatically. The equivalent diameter amounts to $D_{\mathrm{eq}} = \sqrt{0.4^2 + 4 \times 0.16^2}$ = 0.512 m.

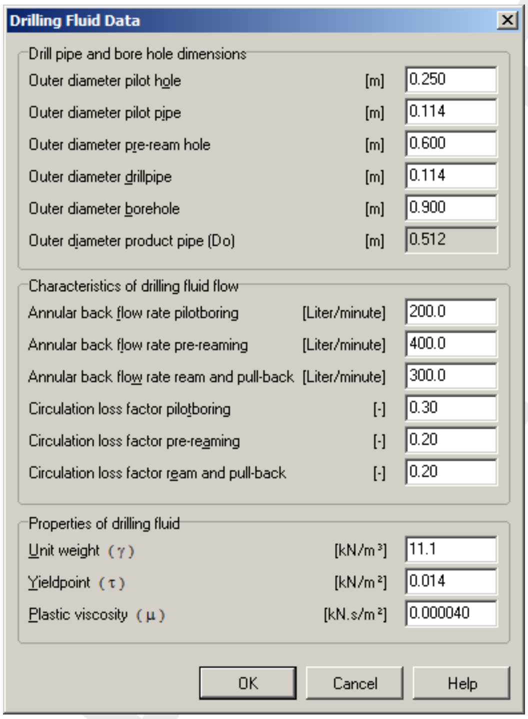


Figure 13.2: *Drilling Fluid Data window*

13.4 Engineering Data

Since the engineering properties for a bundle are different from single pipeline installation properties, values of the engineering properties have to be changed.

18. Click *Data* and select *Engineering data* on the menu bar to select the *Engineering Data* window. This will result in the window shown in Figure 13.3.
19. Do not fill the pipe on the rollers and enter the values of Figure 13.3 in the standard input window.
20. Click on the *OK* button to confirm the input of the specified values.

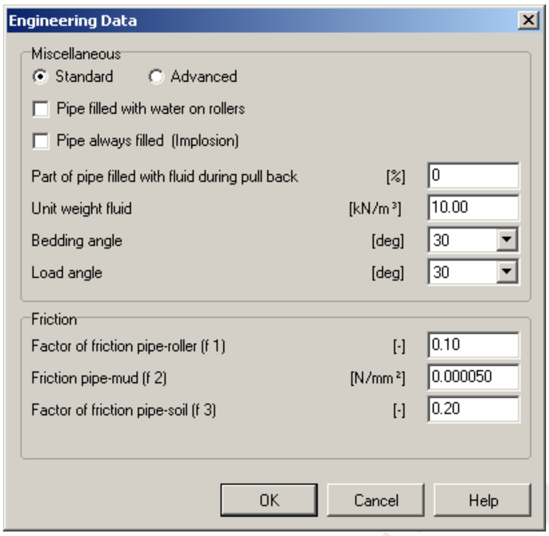


Figure 13.3: *Engineering Data window*

13.5 Factors

D-GEO PIPELINE performs the calculations of the drilling fluid pressures according the Dutch regulations described in the NEN 3650 series (NEN, 2012a,b,c) and in NEN 3651 (NEN, 2012d). The safety philosophy described in the NEN 3650-1 Annex B and D is applied on the calculations.

21. Click *Defaults* and select *Factors* on the menu bar to select the contingency and safety factors window for watching the default values or adapting this values.
22. Due to the pull back of the bundled pipelines the risk on higher pulling forces than calculated is present. According to the NEN 3650-1 (article E.1.2.3), the contingency factor on the pulling force should be 1.8. Change this value into <1.8> as shown in Figure 13.4.
23. Click *OK* to confirm.

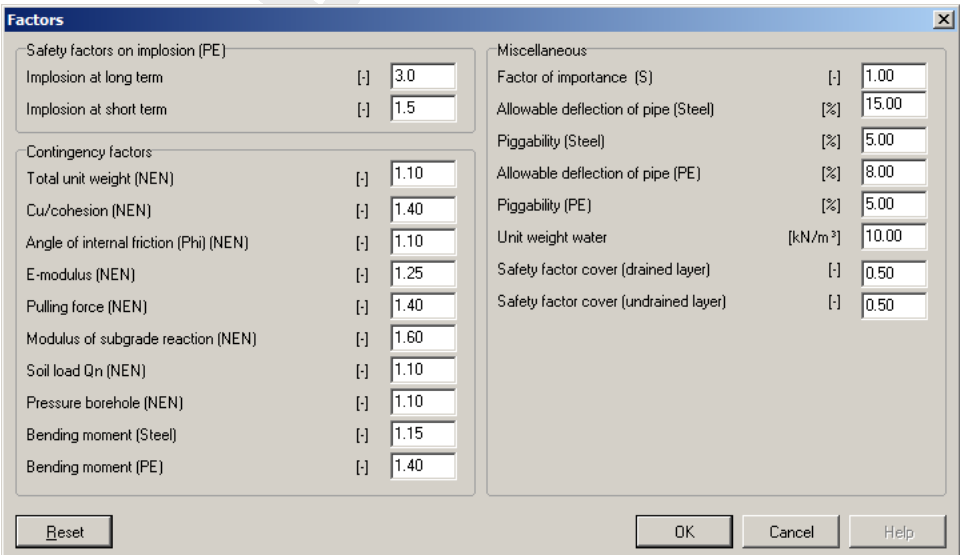


Figure 13.4: *Factors window*

13.6 Results

The results of the pulling force calculation are shown in the report which is created automatically after finishing the calculations.

24. To start the calculations click *Calculation* and select *Start* on the menu bar to tart the calculation or press the function key F9.
25. Click *Results* and select *Report* on the menu bar to view the results of the pulling force calculations. The results can be found in paragraph 5.3 (Figure 13.5).

5.3 Calculation Pulling Force

During the pullback operation the pipe experiences friction which is based on:

- friction between pipe and pipe-roller (f1 = 0.10)
- friction between pipe and drilling fluid (f2 = 0.000050 [N/mm²])
- friction between pipe and soil (f3 = 0.20)

Due to the friction a pulling force is induced in the pipeline.
The pulling direction of the product pipe is from left to right

This calculation takes into account that the length of the pipe on the rollers decreases while pulling back the pipeline. During the pull back operation the bore hole is supposed to be stable.

Characteristic points	Length pipe in bore hole (m)	Expected pulling force (kN)
T1	0	17
T2	25	27
T3	129	71
T4	155	81
T5	260	129
T6	284	138

The calculated pulling force is the mean value. It is recommended to use a contingency factor of at least 1.4 for the stress analysis. In the subsequent pipe stress analysis a factor of 0.00 is used and a load factor of 1.00 (steel only).

Figure 13.5: *Report window, Calculation Pulling Force*

Notice that the total pulling force is divided over the pipelines in the bundle for pipe stress analysis purposes. The pipe stress analysis per pipeline is described in the paragraphs 6 to 10.

14 Tutorial 7: Face support pressure for micro tunneling

This seventh tutorial considers installation of a gas pipeline crossing underneath a railway by using micro-tunneling. The gas pipeline consists of steel pipe sections. The exercise focuses on the basic calculation set up for micro-tunneling in D-GEO PIPELINE.

The objectives of the exercise are:

- ◇ To make a schematization of the pipeline installation by micro tunneling;
- ◇ To evaluate the minimal required and maximal allowable shield pressure at the face of the tunneling machine.

The following modules are needed:

- ◇ D-GEO PIPELINE Standard module (HDD)
- ◇ Micro Tunneling module

The result of this tutorial is presented in the file Tutorial-7.dri.

14.1 Introduction to the case

Micro-tunneling in general uses a remote controlled micro tunnel boring machine (MTBM). The micro tunnel usually starts horizontal at a certain level below the surface. Drive and reception shafts are created for the MTBM. In the drive shaft a jacking frame and MTBM are installed. The jacks will push the pipe section elements section by section ahead towards the reception shaft. The MTBM is at the front of the advancing micro tunnel. As the length of the advancing micro tunnel increases so do the friction forces along the pipe segments. Lubrication fluid may be applied for lubrication.

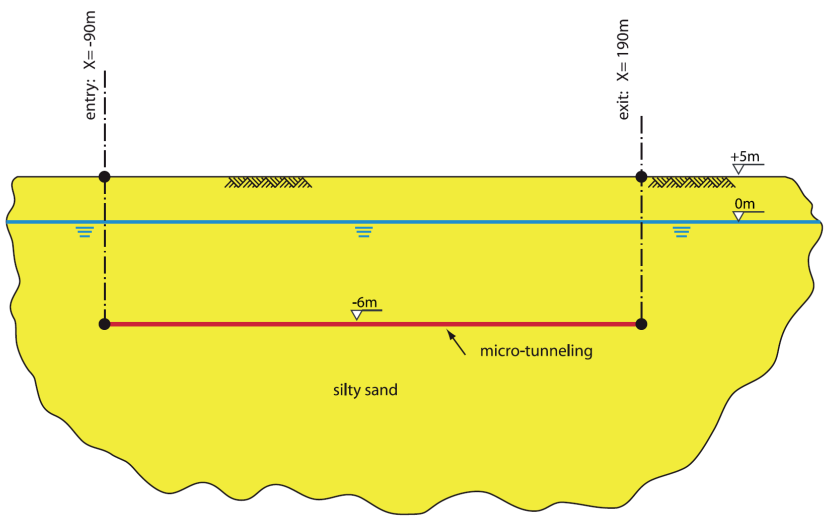


Figure 14.1: *Pipeline configuration for Tutorial 7*

Very often at the face of the MTBM drilling fluid is used for, soil removal and front stabilization. Careful planning and monitoring of the face support pressures is required: When the pressure is excessive this may cause a blow out; if the pressure is too low collapse of the soil in at the drilling front may cause excessive subsidence. The pipeline configuration is shown in Figure 14.1.

The soil properties of the silty sand layer are provided in Table 14.1.

Table 14.1: *Properties of the silty sand layer (Tutorial 7)*

Dry unit weight	[kN/m^3]	18
Wet unit weight	[kN/m^3]	20
Cohesion	[kN/m^2]	0
Angle of internal friction	[°]	30
Undrained strength top	[kN/m^2]	0
Undrained strength bottom	[kN/m^2]	0
E modulus top	[kN/m^2]	10000
E modulus bottom	[kN/m^2]	15000
Adhesion	[kN/m^2]	0
Friction angle (Delta)	[°]	20
Poisson's ratio	[-]	0.35

The pipeline material used in this tutorial is a steel 240 with the properties given in Table 14.2.

Table 14.2: *Properties of steel material (Tutorial 7)*

Pipe material		Steel 240
Outer diameter	[mm]	1200
Overcut	[mm]	15
Wall thickness	[mm]	22.4
Young's modulus	[N/mm^2]	205800
Unit weight pipe material	[kN/m^3]	78.50

This tutorial starts with the selection of the pipeline installation model.

14.2 Model selection

The micro tunneling model must be selected to carry out the current tutorial.

noitemsep

1. Click *File* and choose *New* on the menu bar to start a new project.
2. In the *New File* window select the option *New geometry* to start. This will result in an empty geometry.
3. Save the project by clicking *Save As* in the *File* menu and by entering <Tutorial-7> as project name.
4. Click *Save* to close this window.
5. On the menu bar, click *Project* and then choose *Model* to open the *Model* window (Figure 14.2).
6. Select *Micro tunneling* and click *OK*.

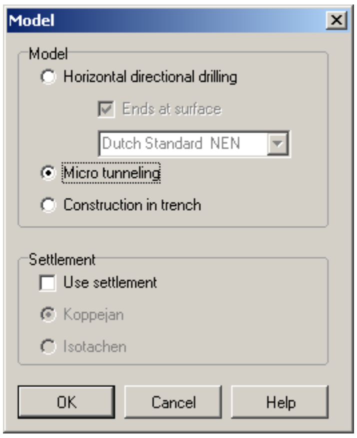


Figure 14.2: *Model window*

7. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
8. Fill in <Tutorial 7 for D-GEO PIPELINE > and <Gas pipeline installation by micro tunneling> for *Title 1* and *Title 2* respectively in the *Identification* tab.
9. In the other tab of the *Project Properties* window, modify (if not already done) some defaults values according to Figure 14.3 in order to make the graphical geometry more understandable.
10. Click *OK*.

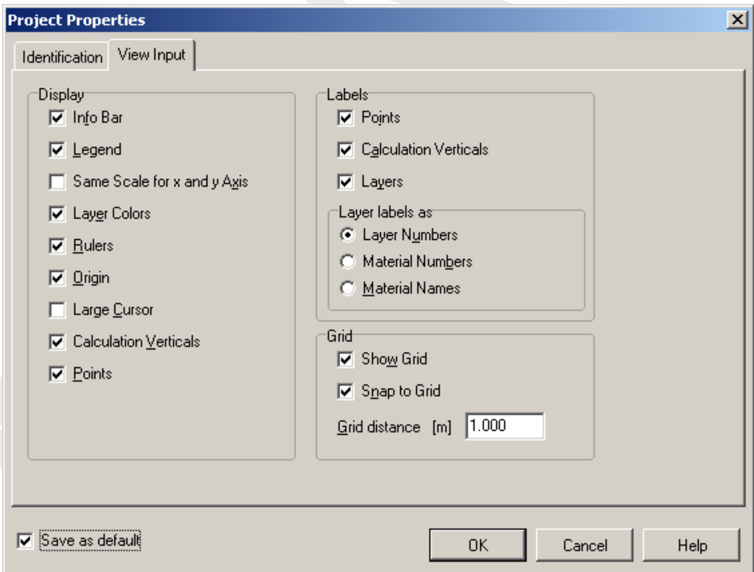


Figure 14.3: *Project Properties window, View input tab*

14.3 Geometry

Firstly, the geometry of Figure 14.1 needs to be given in D-GEO PIPELINE. In order to do this, the following actions should be performed:

11. First enlarge the dimensions of the geometry window by selecting the left boundary by clicking the left mouse button, then click the right button and select *Properties.* This will result in the coordinate window for the left boundary as shown in Figure 14.4. Enter coordinate X of $<$100 m$>$.

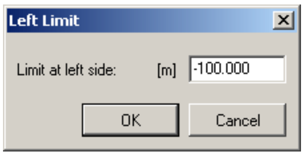


Figure 14.4: *Left Limit window*

12. Repeat the previous described actions for the right boundary and shift the boundary to coordinate X of $<$200 m$>$. The width in between the left and the right boundary is now 300 m.
13. Select the drawing button *Zoom limits* from the *Tools* panel so that the drawn geometry appears in the center of the screen.
14. Unselect the drawing button *Automatic regeneration of geometry on/off* from the *Tools* panel.
15. Select the drawing button from the *Edit* panel *Add single line* to draw the surface line of the longitudinal cross section of the horizontal directional drilling and position the straight surface line at Z = 5 m. Use the right mouse button to finish the line.
16. Select again the drawing button *Add single line* to draw the lower boundary of the longitudinal cross section of the horizontal directional drilling and position the straight lower boundary line at Z = –40 m. Use the right mouse button to finish the line.
17. Select the drawing button *Automatic regeneration of geometry on/off* from the *Tools* panel so that the geometry as shown in Figure 14.5 appears.
18. Select the drawing button *Add pl-line(s)* from the *Edit* panel and position the level of the groundwater at coordinate Z = 0 m. Use the right mouse button to finish the line. The blue dashed line represents the groundwater line (PL line).

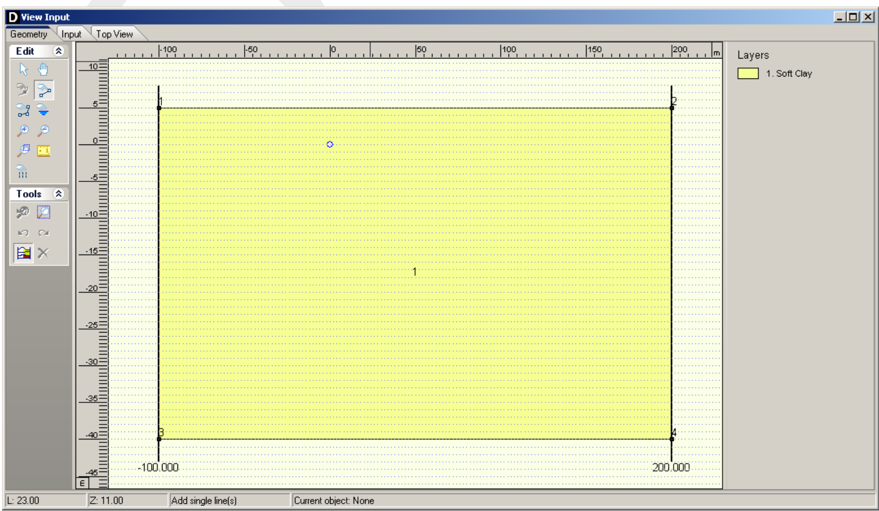


Figure 14.5: *View Input window, Geometry tab*

14.3.1 Soil layer properties

The properties of the soil layers should be specified in the menu materials, which can be entered by clicking soil. In this tutorial only one soil layer is considered.

19. Click *Soil* and select *Materials* on the menu bar to open the *Materials* window (Figure 14.6) and enter the soil data.
20. Add a new material by choosing *Add* button below the materials list on the left side of the window with the new <Silty Sand>.
21. Enter the soil data as given in Table 14.1.
22. Finish the input of soil data by clicking *OK*.

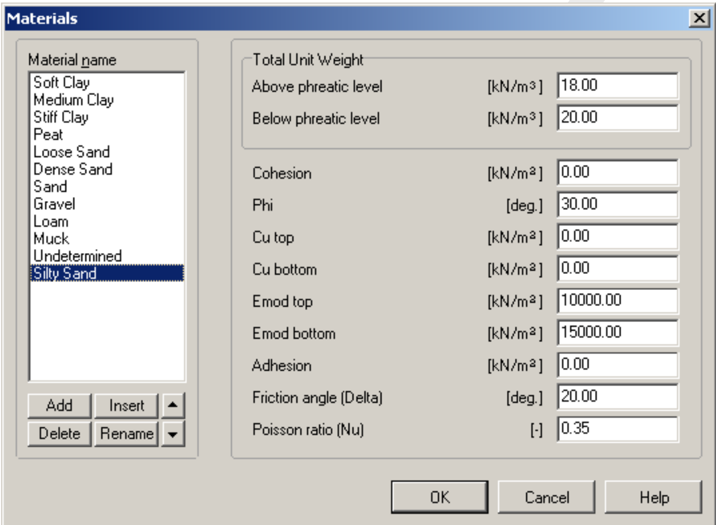


Figure 14.6: *Materials window*

The defined soil properties and the groundwater level have to be assigned to the drawn geometry of the longitudinal cross section. The assignments can be carried out by clicking geometry and choosing the subsequent described options on the menu bar.

14.3.2 Phreatic Line

23. On the *Geometry* menu, select *Phreatic Line* to open *Phreatic Line* window (Figure 14.7) in which the phreatic line for calculation of the groundwater pressures can be selected.
24. Choose PL–line nr. <1> (only one phreatic line is available) and click *OK*.

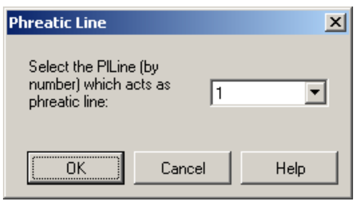


Figure 14.7: *Phreatic Line window*

14.3.3 Layers

25. Click *Geometry* and select *Layers* on the menu bar to assign the soil properties to the soil layers in the longitudinal cross section. To assign a material to a layer, select the *Material* tab.

26. Assign the properties of the defined layer *Silty Sand* to layer nr 1 in the longitudinal cross section. The available soil layers with defined properties are shown in left column of the materials window. The layers in the longitudinal cross section are shown in the right column of the materials window. The defined properties are assigned to layer nr 1 by clicking the arrow in between the columns. This will result in the *Material* tab shown in Figure 14.8.

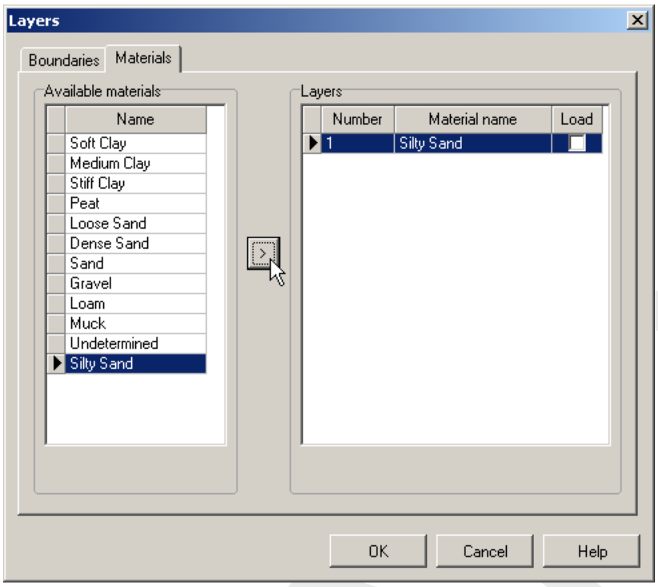


Figure 14.8: *Layers window, Materials tab*

27. Click *OK* to quit the window and return to the geometry window to watch the change of layer name in the legend.

14.3.4 PL-Lines per Layers

28. Click *Geometry* and select *PL–lines per Layers* on the menu bar to open the *PL–lines per Layer* window (Figure 14.9) in which the defined PL–lines to the soil layers in the longitudinal cross section can be defined. This window contains the information for the calculation of the groundwater pressure distribution. In this tutorial only one PL-line is defined. The groundwater pressure at the top of the silty sand layer and the bottom of this layer should be calculated based on the hydraulic head of PL-line 1.
29. Click *OK* to close the window.

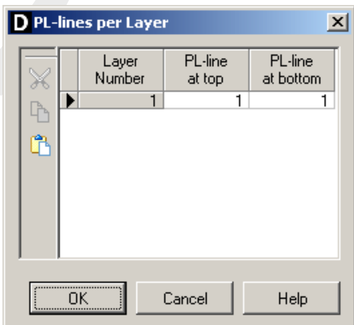


Figure 14.9: *PL-lines per Layers window*

14.3.5 Check Geometry

30. The geometry can be tested by clicking *Geometry* and selecting *Check Geometry* on the menu bar. If the geometry is entered properly, the message shown in Figure 14.10 appears.
31. Click *OK* to close the window.

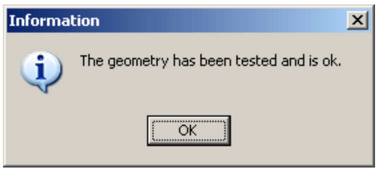


Figure 14.10: *Check Geometry window*

14.4 Pipeline Configuration

The pipe is installed in the silty sand layer starting and ending at respectively the start and reception shaft at a level 11 m below surface. As the pipe trajectory is horizontal, the smallest angle of entry allowed by D-GEO PIPELINE is defined, i.e. 0.1 degree. A small bending radius restricts the curved part of the pipe near the entry and exit of the pipe, thus the rest of the pipe will be exact along the lowest level of the pipe.

32. Click *Pipe* from the menu and select *Pipeline Configuration* to open the *Pipeline Configuration* window.
33. Enter the values as presented in Figure 14.11.

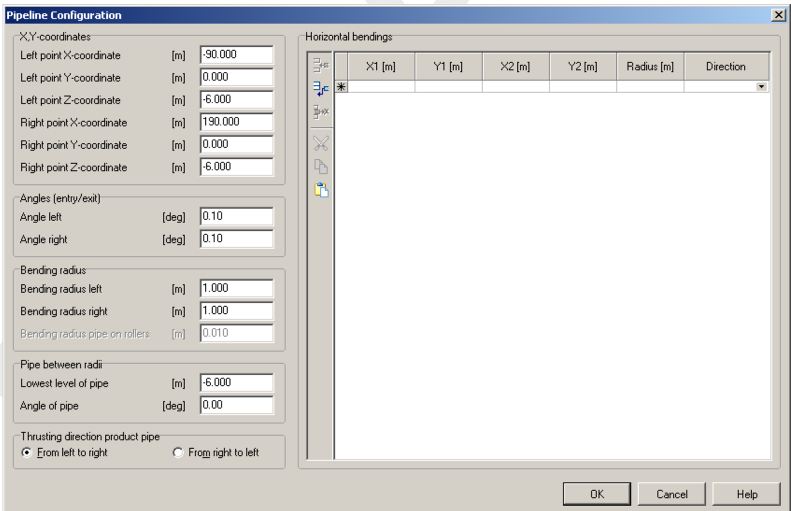


Figure 14.11: *Pipeline Configuration window*

34. Click *OK* to confirm.
35. Now examine the micro tunnel trajectory in the *Input* tab (Figure 14.12) and *Top View* tab of the *View Input* window.

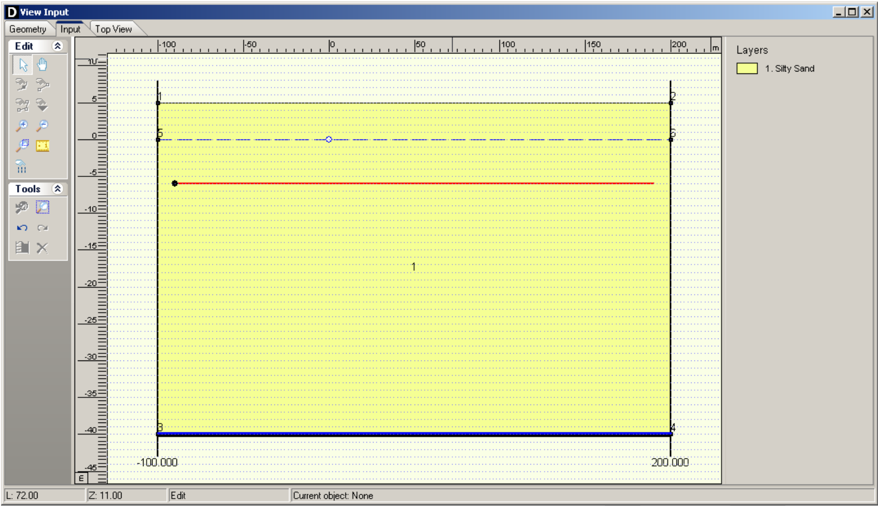


Figure 14.12: *View Input window, Input tab*

14.5 Pipe Material Data

The pipe material of the pipe which will be installed by micro tunneling is chosen. The characteristics of the pipe must be specified as well.

36. Click *Pipe* from the menu and select *Product Pipe Material Data* to open the *Product Pipe Material Data* window.
37. Enter the values as presented in Figure 14.13.

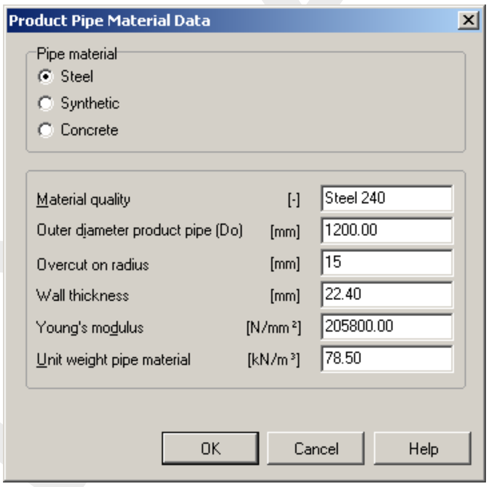


Figure 14.13: *Product Pipe Material Data window*

The effect of the overcut on the radius of the pipe is explained in tutorial 9 (chapter 16).

14.6 Soil behavior

The strength of soil layers is dependent on the drained or undrained behavior of soil layers during application the drilling fluid pressure at the front of the MTBM. Depending on the permeability of the soil layer, the soil will behave drained or undrained. A Sand layer is a well permeable so called drained frictional material. The strength of this soil layer can be calculated using the drained (effective) strength parameters effective cohesion (c) and angle of internal friction (φ). In case of undrained behavior in other soil types, the strength of the soil

can be calculated using the undrained strength parameter undrained cohesion (c_{u}).

38. Click *GeoObjects* and select *Boundaries Selection* on the menu bar to open the *Boundaries Selection* window for specification of the soil behavior.
39. Choose the boundary between the undrained and drained layer on top of layer nr $<1>$ (Figure 14.14). This choice results in drained behavior of layer nr 1.
40. Choose the boundary between the compressible and incompressible layer on top of layer nr $<1>$. This choice results is used for the calculation of the soil mechanical parameters. Compressible layers yield higher soil loads on the pipeline due to incomplete arching.
41. Click *OK* to close this window.

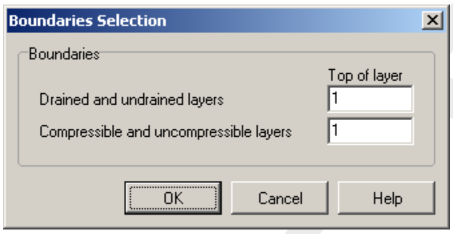


Figure 14.14: *Boundaries Selection window*

14.7 Calculation Verticals

The locations in the longitudinal cross section at which a calculation should be carried out must be specified by the user. The user is able to perform calculations at uniform distances along the longitudinal cross section but is also able to perform more calculations at short distances at locations of interest.

42. Click *GeoObjects* and select *Calculation Verticals* on the menu bar to select the *Calculation Verticals* window for specification of the calculation locations along the longitudinal cross section.
43. Choose the *Automatic generation of L co-ordinates* option on the right side of the window and choose the following values: $<$–80 m$>$ for *First*, $<$180 m$>$ for *Last* and $<$20 m$>$ for *Interval*.
44. Click on the *Generate* button and watch the result of automatic vertical generation on the left side of the *Calculation Verticals* window. This will result in the window shown in Figure 14.15.
45. Click *OK* to confirm the selected verticals and switch to the input window to watch the location of the verticals in the longitudinal cross section.

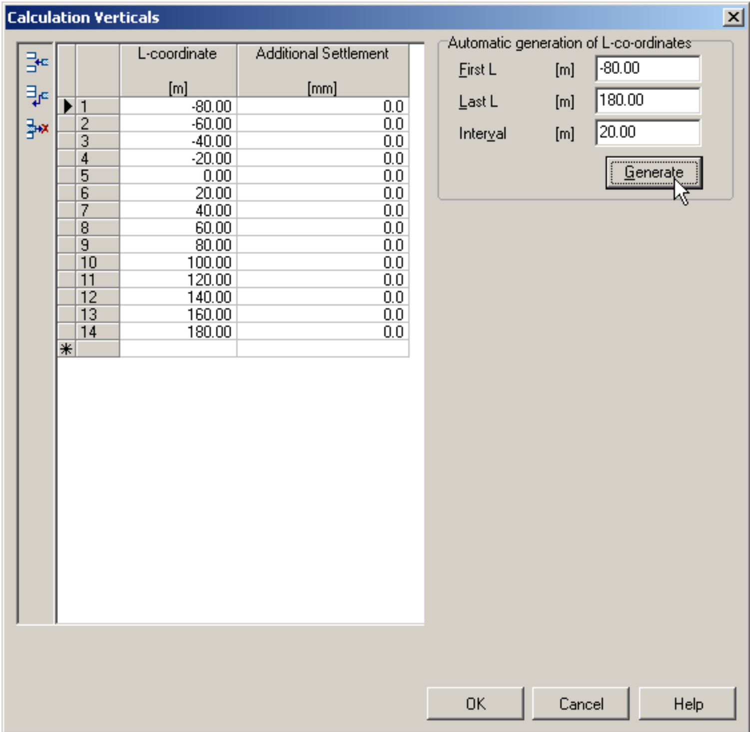


Figure 14.15: *Calculation Verticals window*

14.8 Engineering Data

46. Select *Engineering Data* from the *Pipe* menu bar to open the *Engineering Data* window.
47. Enter the values as given in Figure 14.16.

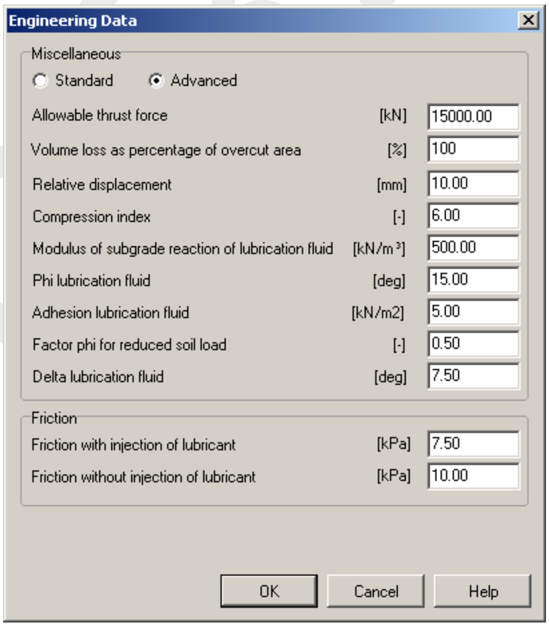


Figure 14.16: *Engineering Data window*

The maximum allowable thrust force is usually specified by the manufacturer of the pipe. The volume loss determines the subsidence at the surface.

14.9 Results: Operation Parameter Plots

The micro-tunneling machine changes the stress conditions in the soil. The deviations from the original stress conditions (Figure 14.17) are largely determined by the size of the overcut and the applied shield. Small deviations from the original conditions are acceptable as the stability of soil adjacent to the micro-tunneling machine is maintained. A relative low face support pressure may lead to collapse of the soil in front of the shield, which in turn may lead to subsidence of the surface or to settlement of soil layers below a construction or pipeline. A relatively high face support pressure can lead to a blow out of drilling fluid or may lead to heave of the surface.

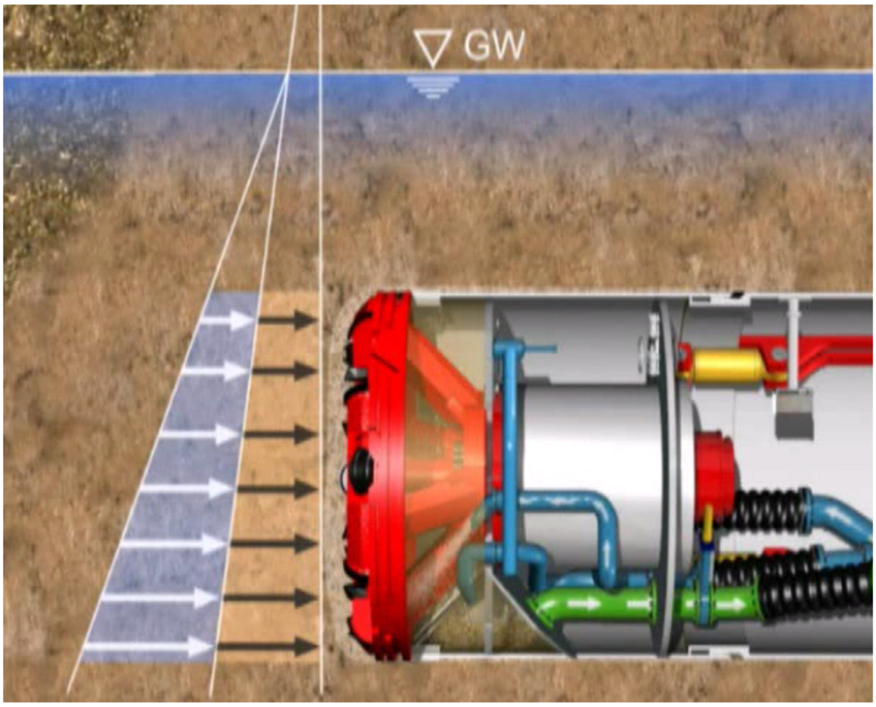


Figure 14.17: *Schematization of stress condition for micro-tunneling*

While drilling the shield pressures have to be kept between certain limits. To prevent the possibility of collapse in of the soil in front of the micro tunneling shield, causing subsidence, the soil at the front is kept stable by maintaining a minimal face pressure. Depending on the soil type the minimal support pressure can be calculated using Jancsecz and Steiner theory (drained behavior of the soil) (Jancesz and Steiner, 1994), or Broms and Bennermark theory (undrained behavior of the soil) (Broms and Bennermark, 1967). In this tutorial the soil layer which consists of silty sand exhibits drained soil behavior.

A maximum support pressure should not be exceeded to prevent uplift of the soil above the micro-tunneling machine or a blow out of drilling fluid towards the surface. The support pressure, at which the soil deformations are minimal during drilling should be in between the two limits. At the neutral pressure, the face support pressure is in equilibrium with the current horizontal soil pressure.

48. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.
49. Click *Results* and select *Operation Parameter Plots* from the menu bar to open the *Operation Parameter Plots* window.

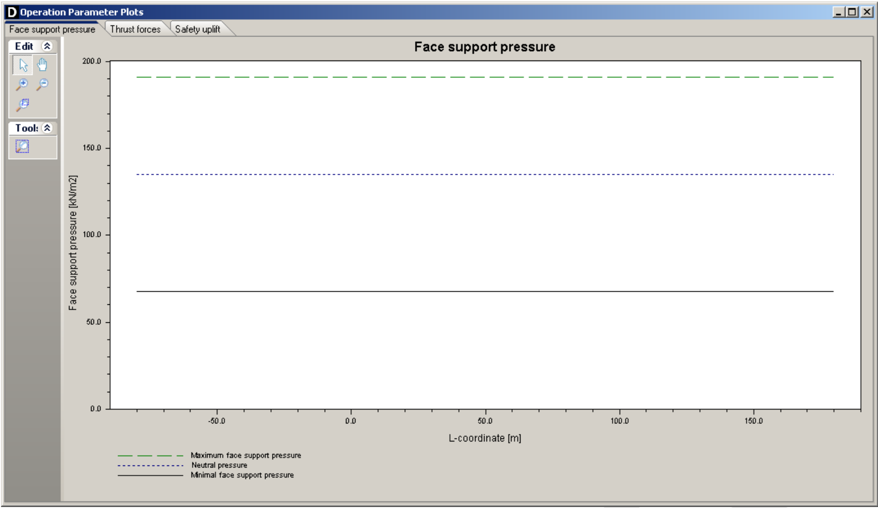


Figure 14.18: *Operation Parameter Plots window, Face support pressure tab*

From the graph (Figure 14.18) it can be observed that for this simple tutorial situation the target face support pressure during the pipeline installation should be between the determined limits of the maximum allowable face support pressure and the minimum required face support pressure. At the neutral pressure the face support pressure is in equilibrium with the current horizontal soil pressure.

15 Tutorial 8: Uplift and thrust forces for micro tunneling

This tutorial concentrates on the installation of a pipeline by using the micro-tunneling technique and is a continuation of the previous tutorial. It considers installation of a gas pipeline consisting of welded steel pipes. The pipeline crosses underneath a railway by using micro-tunneling.

The objectives of the exercise are:

◇ To evaluate the thrust force;
◇ To perform a check on the uplift safety.

The following modules are needed:

◇ D-GEO PIPELINE Standard module (HDD)
◇ Micro Tunneling module

This tutorial is presented in the file Tutorial-8.dri.

15.1 Introduction to the case

This tutorial considers a peat layer on top of the existing silty sand layer. The risk on uplift of the empty pipeline in the peat layer is evaluated. The possibility of an alternative, longer, micro tunneling trajectory is evaluated in this tutorial. A longer pipe string yields increased friction forces which could possibly exceed the maximum allowable thrust force of the pipeline or the jacking frame.

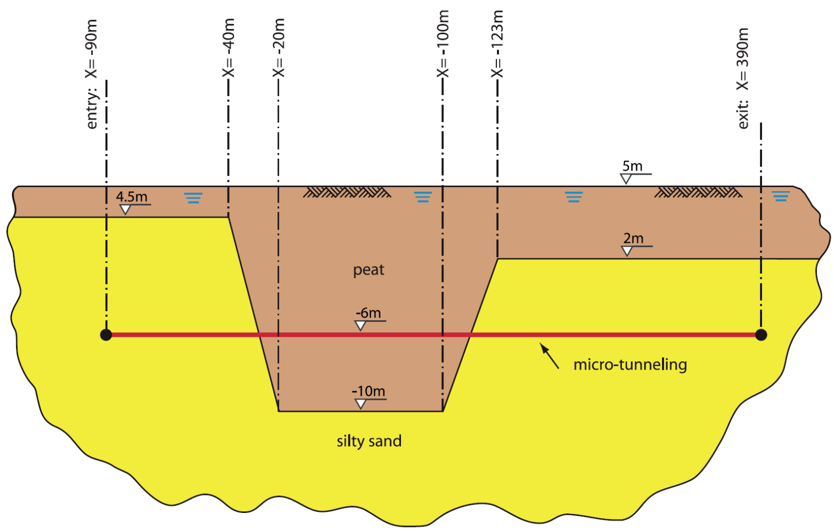


Figure 15.1: *Soil layers and pipeline configuration for Tutorial 8*

The soil properties are provided in Table 15.1.

Table 15.1: *Properties of the layers (Tutorial 8)*

		Silty Sand	**Peat**
Dry unit weight	[kN/m^3]	18	10.2
Wet unit weight	[kN/m^3]	20	10.2
Cohesion	[kN/m^2]	0	2
Angle of internal friction	[°]	30	15
Undrained strength top	[kN/m^2]	0	10
Undrained strength bottom	[kN/m^2]	0	20
E modulus top	[kN/m^2]	10000	1000
E modulus bottom	[kN/m^2]	15000	1500
Adhesion	[kN/m^2]	0	2
Friction angle (Delta)	[°]	20	5
Poisson's ratio	[-]	0.35	0.45

This tutorial is based on continuation of the file used in Tutorial 7 (chapter 14).

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select *Tutorial-7* and click the *Open* button to open the file.
3. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-8>.
4. Click the *Save* button to save the file for Tutorial 8.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 8 for D-GEO PIPELINE > and <Micro tunneling: uplift and thrust forces> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

15.2 Geometry of the longitudinal cross section

This tutorial considers a layered soil sequence. The typical Dutch soil sequence of a peat layer on top of a silty sand layer will be considered. The peat layer is compressible and exhibits a low permeability, while the sand layer is assumed incompressible and exhibits a high permeability. The new soil layers should be specified in the geometry window.

8. In the *View Input* window, switch to the *Geometry* tab to edit the existing soil layer sequence.
9. Click the *Add polyline(s)* button from the *Edit* panel to draw an additional line which represents the lower boundary of the peat layer on top of the silty sand layer. The coordinates of the cursor are given in the lower left side of the geometry window. Make the polyline by clicking on the subsequent co-ordinates (Figure 15.2). Click the right mouse button to escape from the polyline drawing.

	L Co-ordinate [m]	Z Co-ordinate [m]
1	-100.000	4.500
2	-40.000	4.500
3	-20.000	-10.000
4	100.000	-10.000
5	123.000	2.000
6	200.000	2.000

Figure 15.2: *Co-ordinates of the lower boundary of the Peat layer (before enlarging the right limit)*

10. After finishing the polyline, mis-clicks can be corrected using the *Edit* button: select points of the polyline by clicking on it with the left mouse button. Once the point is selected (indicated with a red color), use the right mouse button to select the option *Properties...* and to correct the co-ordinates of the lower boundary of the peat layer.
11. Change the position of the phreatic groundwater: select both points of the PL line (i.e. blue dashed line) by clicking on it with the left mouse button, then select the option *Properties...* and change the co-ordinate into Z = 5 m.
12. Enlarge the dimensions of the geometry window by selecting the right boundary by clicking the right mouse button, then click the right button and select *Properties...*. This will result in the coordinate window for the right boundary as shown in Figure 15.3. Enter coordinate X of $<$400 m$>$.

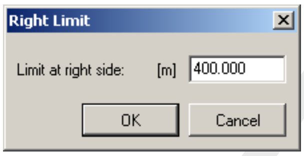


Figure 15.3: *Right Limit window*

13. Click the *Zoom limits* button from the *Tools* panel so that the drawn geometry appears in the center of the screen.

15.3 Soil layer properties

The properties of the soil layers in the layered soil sequence should now be specified.

14. Click *Soil* and select *Materials* on the menu bar to enter the soil data.
15. Select the existing soil material *Peat*.
16. Enter the soil data as given in Table 15.1.
17. Click *OK*.

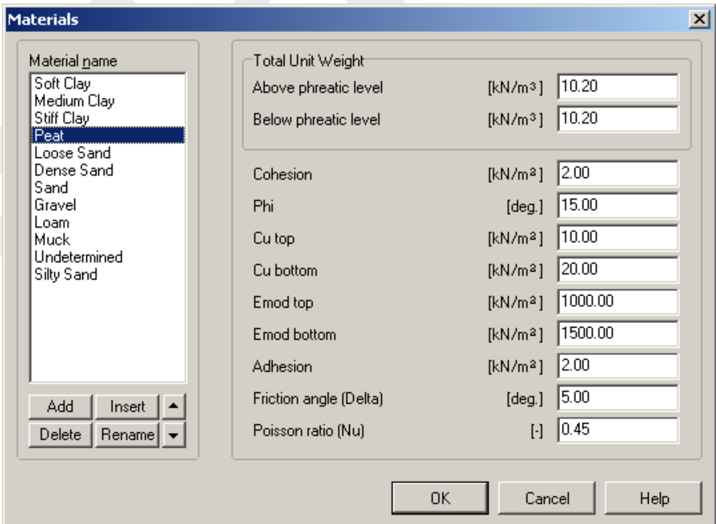


Figure 15.4: *Materials window*

The defined soil properties have to be assigned to the drawn geometry of the longitudinal cross section. The assignments can be carried out in the *Geometry* menu.

18. Click *Geometry* and select *Layers* on the menu bar to open the *Layers* window.

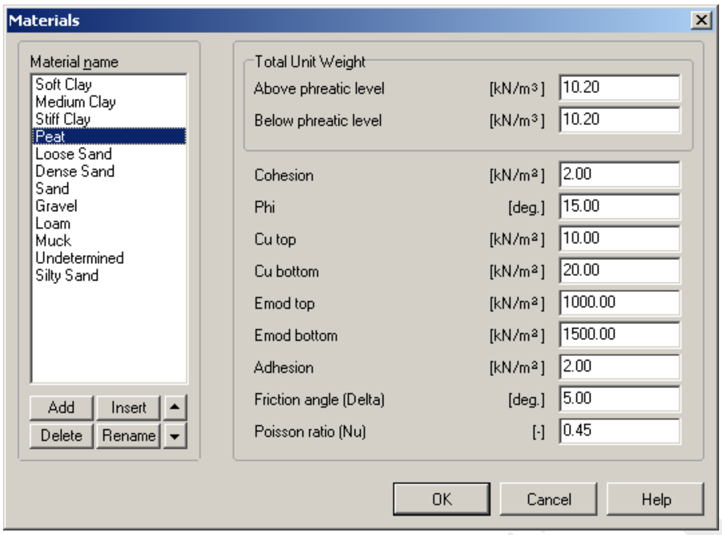


Figure 15.5: *Layers window, Materials tab*

19. Select the *Materials* tab.
20. Assign the properties of the defined layer *Peat* to layer number 2 in the longitudinal cross section by clicking the *Assign* icon in between the left and the right column.
21. Click on the *OK* button to quit the window and return to the *Geometry* tab of the *View Input* window to look at the change of layers name in the legend (Figure 15.6).

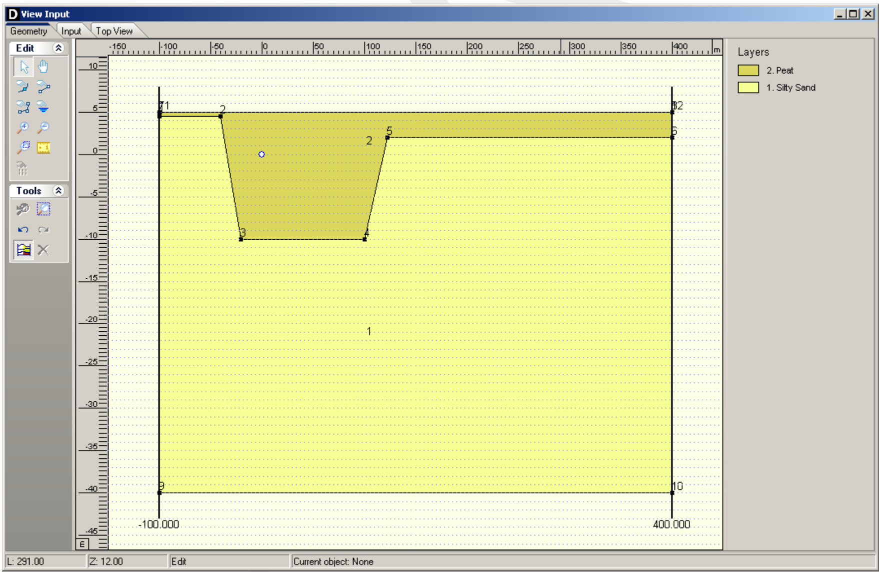


Figure 15.6: *View Input window, Geometry tab*

22. The geometry can be tested by clicking *Geometry* on the menu bar and selecting *Check Geometry*. If the geometry is entered properly, the message *Geometry has been tested and is OK* appears.
23. Click *OK* to close this window.

15.4 Soil behavior

Strength of soil layers is dependent on the drained or undrained behavior of soil layers during application the drilling fluid pressure. Depending on the permeability of the soil layer, the soil will behave drained or undrained. The *Silty Sand* layer is well permeable so that the behavior

of the silty sand layer is drained. The strength of this soil layer can be calculated using the drained (effective) strength parameters effective cohesion (c) and angle of internal friction (φ). In case of undrained behavior in the impermeable *Peat* layer, the strength of the soil can be calculated using the undrained strength parameter undrained cohesion (c_u).

The soil load on the pipeline after finishing the installation is dependent on the soil pipeline interaction, which is in turn largely dependent on the soil behavior. As described in section 10.2 arching develops completely in incompressible soil layers, while in compressible layers the reduced soil load on the pipeline is higher due to compression of the soil next to the pipeline.

24. Click *GeoObjects* and select *Boundaries Selection* on the menu bar to open the *Boundaries Selection* window for specification of the soil behavior.
25. Choose the boundary between the *Drained and undrained layers* on top of layer number $<$1$>$ (Figure 15.7). This choice results in drained behavior of layer number 1.
26. Choose the boundary between the *Compressible and uncompressible layers* on top of layer number $<$1$>$. This choice results in full development of arching in layer number 1 while in layer number 2 arching is not fully developed.
27. Click *OK* to close this window.

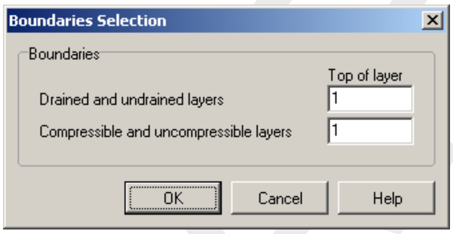


Figure 15.7: *Boundaries Selection window*

15.5 Pipeline Configuration

The tunneling length will be increased by changing the entry and exit locations.

28. Click *Pipe* and select *Pipeline Configuration* from the menu bar to open the *Pipeline Configuration* window.
29. Change the X-coordinates of the left and right points to respectively $<$-90$>$ and $<$390$>$ as shown in Figure 15.8.
30. Click *OK*.

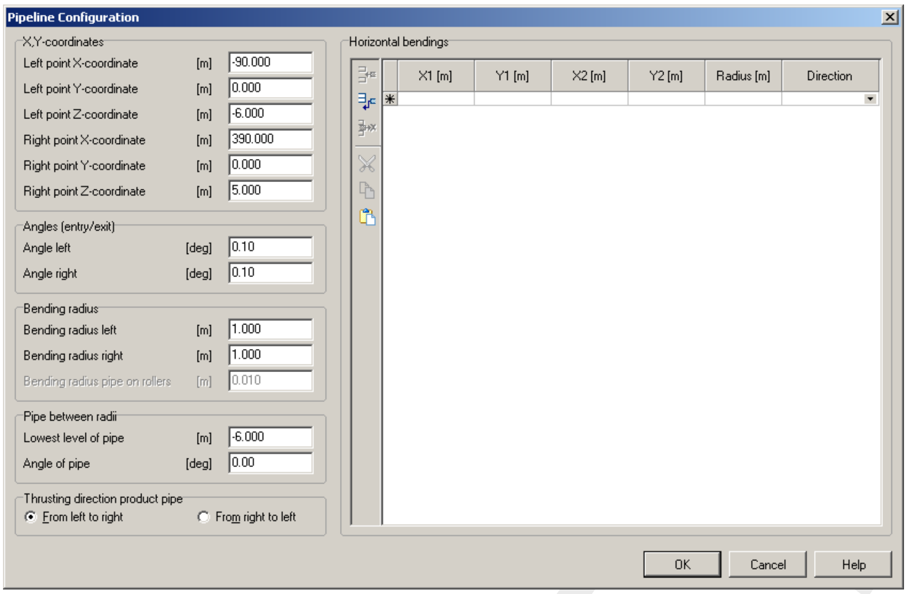


Figure 15.8: *Pipeline Configuration window*

15.6 Calculation Verticals

The locations in the longitudinal cross section at which a calculation should be carried out must be specified by the user. The user is able to perform calculations at uniform distances along the longitudinal cross section but is also able to perform more calculations at short distances at areas of interest.

31. Click *GeoObjects* and select *Calculation Verticals* on the menu bar to select the *Calculation Verticals* window for specification of the calculation locations along the longitudinal cross section. This will result in the window shown in Figure 15.9.
32. Choose the *Automatic generation of L co-ordinates* option on the right side of the window and choose the following values: <–80 m> for *First*, <380 m> for *Last* and <20 m> for *Interval*.
33. Click on the *Generate* button and watch the result of automatic vertical generation on the left side of the *Calculation Verticals* window.
34. Click *OK* to confirm the selected verticals and switch to the input window to watch the location of the verticals in the longitudinal cross section.

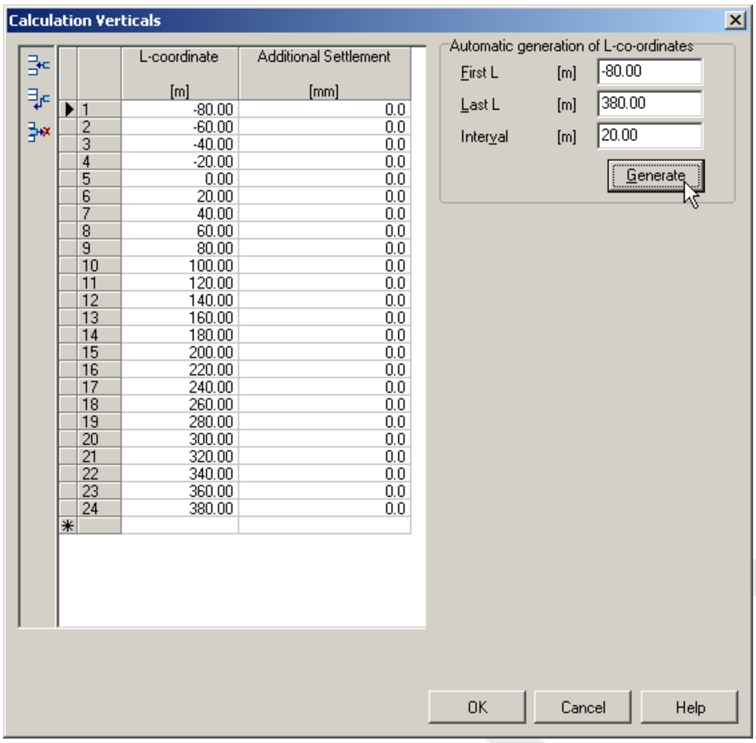


Figure 15.9: *Calculation Verticals window*

15.7 Engineering Data

35. Select *Engineering Data* from the *Pipe* menu bar to open the *Engineering Data* window.
36. Enter the values as given in Figure 15.10.
37. Click *OK*.

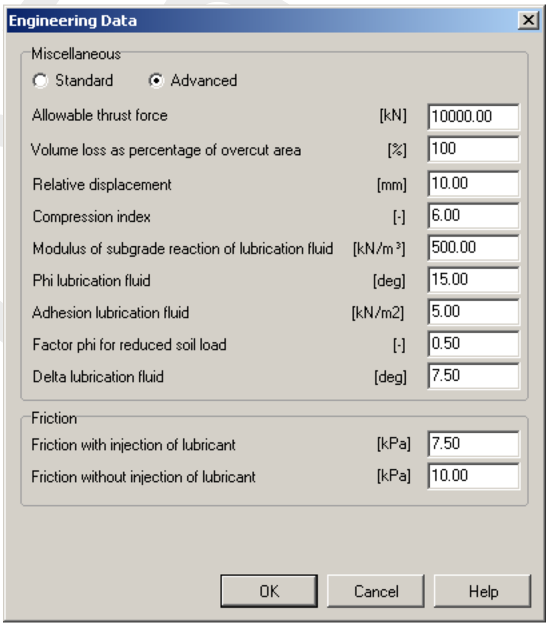


Figure 15.10: *Engineering Data window*

15.8 Results

The schematization of the longitudinal cross section along the pipeline which will be installed by using micro tunneling is changed. A calculation can now be performed.

38. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.

15.8.1 Thrust Force

39. Open the *Operation Parameter Plots* window from the *Results* menu and select the *Thrust forces* tab (Figure 15.11).

This graph shows the calculated thrust force versus the length of pipe jacked into the subsurface. It is easily recognized that the lubricated as well as the dry thrust force exceed the maximum allowable thrust force as indicated by the manufacturer of the pipe sections.

It should be mentioned that the capacity of the jacks is limited as well. In general the maximum capacity is about 600 ton (6000 kN) so that for larger lengths intermediate jacks are required.

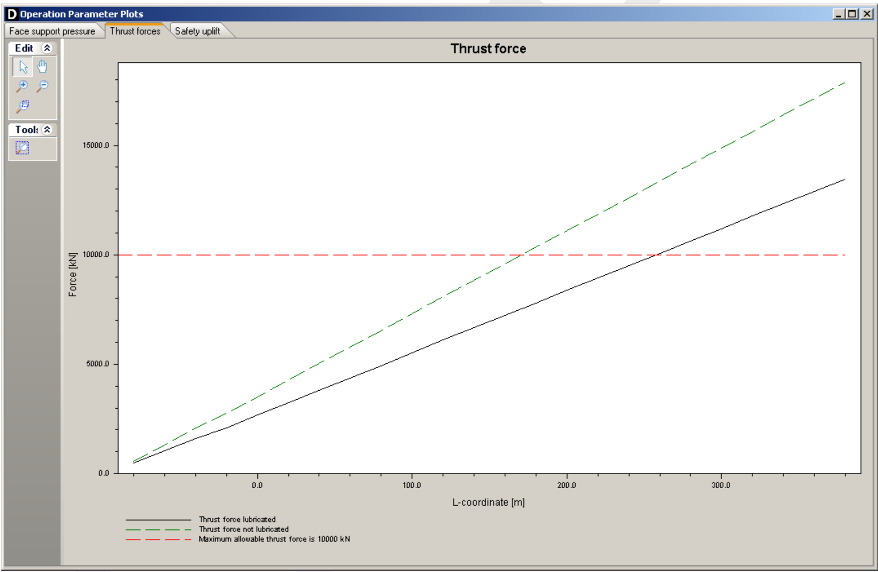


Figure 15.11: *Operation Parameter Plots window, Thrust Force tab*

15.8.2 Uplift safety

Since the pipeline is installed in a soft soil layer with a relative low wet density. The uplift behavior of the empty pipeline should be evaluated. D-GEO PIPELINE calculates the uplift safety factor f_{uplift} using the following formula:

$$f_{\text{uplift}} = \frac{\sigma'_{\text{v}} + g_{\text{pipe}}}{g_{\text{uplift}}} \tag{15.1}$$

where:

σ'_{v}	is the vertical effective stress;
g_{pipe}	is the buoyancy of the pipe depending on the diameter of the pipeline and the water level. Partial submerging is taken into account by D-GEO PIPELINE;
g_{uplift}	is the uplift force.

40. Select the *Safety uplift* tab. As can be seen in Figure 15.12, the uplift safety is more than the required safety factor of 1.

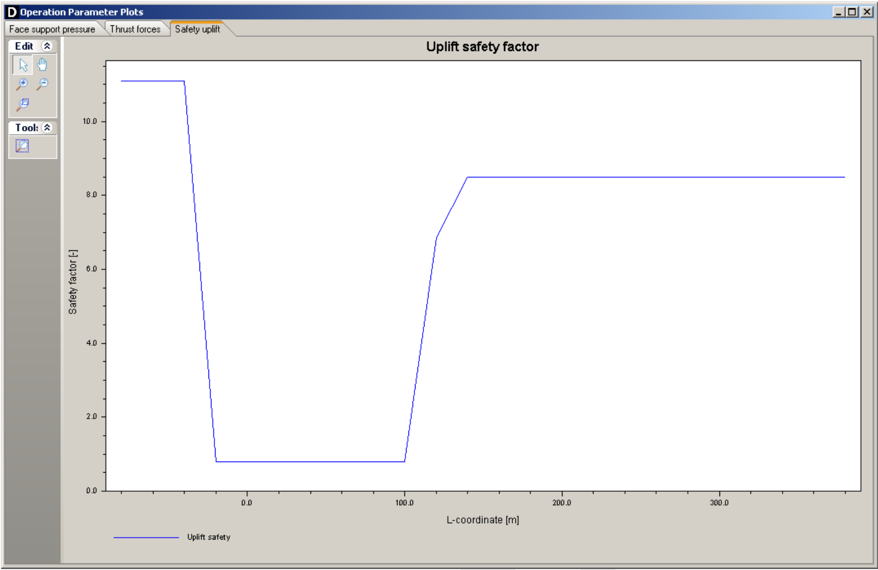


Figure 15.12: *Operation Parameter Plots window, Safety uplift tab*

The uplift safety appears to be insufficient in the peat layer. The uplift safety factor equals 0.8. The safety factors are shown in the report in paragraph 4.2.1. The reported table is shown subsequently.

4.2 Uplift Check

Due to buoyancy of the pipeline below the groundwater table, the uplift should be checked. In the subsequent calculation the safety factor for uplift is calculated based on an empty pipe.

4.2.1 Uplift Factors

Vertical nr.	Safety factor calculated [-]	Safety factor required [-]
1	11.09	1.00
2	11.09	1.00
3	11.09	1.00
4	0.80	1.00
5	0.80	1.00
6	0.80	1.00
7	0.80	1.00
8	0.80	1.00
9	0.80	1.00
10	0.80	1.00
11	6.86	1.00
12	8.49	1.00
13	8.49	1.00
14	8.49	1.00
15	8.49	1.00
16	8.49	1.00
17	8.49	1.00
18	8.49	1.00
19	8.49	1.00
20	8.49	1.00
21	8.49	1.00
22	8.49	1.00
23	8.49	1.00
24	8.49	1.00

Figure 15.13: *Report window, Uplift Factors section*

16 Tutorial 9: Settlement and soil mechanical parameters for micro tunneling

This tutorial provides some detail on settlement and calculation of soil mechanical parameters in D-GEO PIPELINE. For a pipe stress analysis the knowledge of the soil-pipeline interaction is required. The soil pipeline interaction is described by the soil mechanical parameters. The vertical displacement (very often settlement) of the layers below and around the pipeline is one of the soil mechanical parameters.

The objectives of the exercise are:

- ◇ To calculate the soil mechanical parameters
- ◇ To calculate the settlements due to construction of an embankment

The following modules are needed:

- ◇ D-GEO PIPELINE Standard module (HDD)
- ◇ Micro Tunneling module
- ◇ License for D-SETTLEMENT (formerly known as MSettle)

This tutorial is presented in the file Tutorial-9.dri.

16.1 Introduction to the case

The same project as Tutorial 8 (chapter 15) is considered with an additional load carry on the compressible soil layers (Figure 16.1). Settlement can be therefore expected.

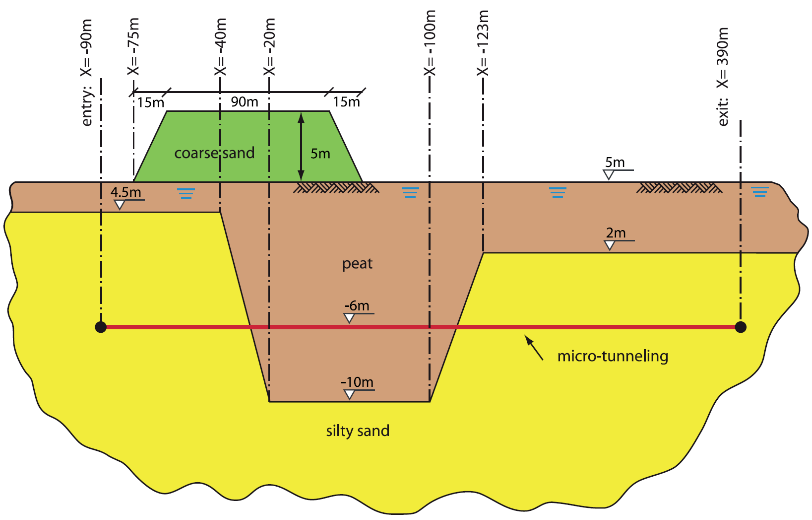


Figure 16.1: *Soil layers and pipeline configuration for Tutorial 9*

For advanced pipe stress analyses special programs need to be used. These programs need an advanced set of soil mechanical parameters, provided by D-GEO PIPELINE. The programs will generate a complete spring model around the pipeline for further analyses. The soil mechanical parameters provided by D-GEO PIPELINE are:

- ◇ neutral vertical soil load
- ◇ passive vertical soil load

- ◇ reduced vertical soil load
- ◇ vertical modulus of sub grade reaction
- ◇ horizontal modulus of sub grade reaction
- ◇ ultimate vertical bearing capacity
- ◇ ultimate horizontal bearing capacity
- ◇ neutral horizontal soil load
- ◇ vertical displacement
- ◇ maximal axial friction
- ◇ friction displacement

Vertical displacement of soil below and around the pipeline that occurs after installation is an important factor in assessing the stresses in the pipeline. Settlement may be entered manually if the vertical settlements results are available. For more accurate results, D-GEO PIPELINE can use the D-SETTLEMENT computer program (formerly known as MSettle) without additional input. Settlement deals with soil compaction due to imposed loading. In D-GEO PIPELINE the loading consists of an extra layer as created in the geometry. The calculation of the settlement is performed externally by D-SETTLEMENT, the settlement calculation program of the Deltares Systems tools. Details on the calculation of settlement are beyond the scope of this manual, a thorough description can be found in the user manual of D-SETTLEMENT (Deltares).

Table 16.1: *Settlement parameters (acc. Koppejan) of the soil layers (Tutorial 9)*

	Coarse Sand	**Silty Sand**	**Peat**
Over-consolidation ratio (OCR)	1	1.3	1.3
Primary compression coeff. below Pc (C_p)	10^9	10^9	40
Primary compression coeff. above Pc (C_p')	10^9	10^9	10
Secondary compression coeff. below Pc (C_s)	10^9	10^9	160
Secondary compression coeff. above Pc (C_s')	10^9	10^9	35

This tutorial is based on the geometry made in Tutorial 8.

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select *Tutorial-8* and click the *Open* button to open de file.
3. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into $<$Tutorial-9$>$.
4. Click the *Save* button to save the file for Tutorial 9.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in $<$Tutorial 9 for D-GEO PIPELINE $>$ and $<$Micro tunneling: settlement and soil mech. param.$>$ for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

16.2 Settlement

For calculation of settlement a license for D-SETTLEMENT is required. If this license and software is available the model option *Settlement* will be available in D-GEO PIPELINE. For this purpose an embankment that will act as a load is introduced.

Settlement calculations can be performed using the in the Netherlands often used Koppejan model or the more recent developed Isotache model which is based on Terzaghi's settlement model.

8. Click *Project* and select *Model* on the menu bar to open the *Model* window.

9. Mark the *Use settlement* check-box and select the *Koppejan* model (Figure 16.2).
10. Click *OK* to confirm the choice.

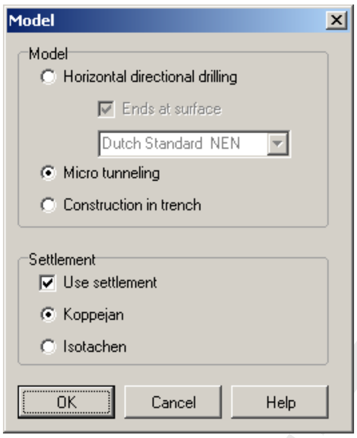


Figure 16.2: *Model window*

16.3 Geometry of the longitudinal cross section

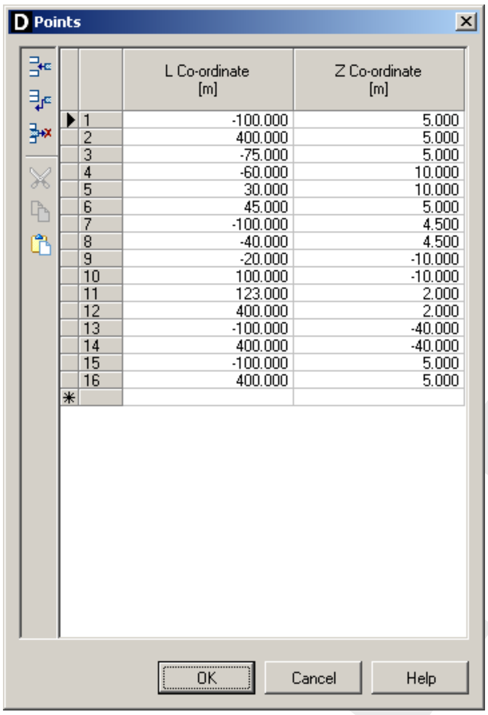
This tutorial considers a layered soil sequence described in Tutorial 8 (chapter 15). In the longitudinal cross section, a load (soil mass) has to be defined.

11. Switch to the *Geometry* tab in the *View Input* window to edit the existing soil layer sequence.
12. Select the *Add polyline* icon from the *Edit* sub-window to draw an additional layer (soil mass) on top of the existing soil layers with coordinates given in Table 16.2.

Table 16.2: *Coordinates of the top of the soil mass*

X co-ordinate [m]	Z co-ordinate [m]
-75	5
-60	10
30	10
45	5

13. Quit editing by clicking the right mouse button.
14. To check or modify the added points, select a point by clicking the left mouse button. The point will become a red square.
15. Click the right-hand mouse button and select *Properties...*. In the window displayed (Figure 16.3), the co-ordinates can be checked and modified if needed.



	L Co-ordinate [m]	Z Co-ordinate [m]
1	-100.000	5.000
2	400.000	5.000
3	-75.000	5.000
4	-60.000	10.000
5	30.000	10.000
6	45.000	5.000
7	-100.000	4.500
8	-40.000	4.500
9	-20.000	-10.000
10	100.000	-10.000
11	123.000	2.000
12	400.000	2.000
13	-100.000	-40.000
14	400.000	-40.000
15	-100.000	5.000
16	400.000	5.000

Figure 16.3: *Points window*

16. Click the *Zoom limits* button from the *Tools* panel so that the drawn geometry appears in the center of the screen.
17. Select the *Automatic regeneration of geometry on/off* icon from the *Tools* sub-window so that the geometry as shown in Figure 16.4. If the *Automatic regeneration of geometry* icon already is selected, click on the *Edit* icon to regenerate the geometry. Notice that the soil mass is located on the left side above the section where the pipeline is located in the peat layer.

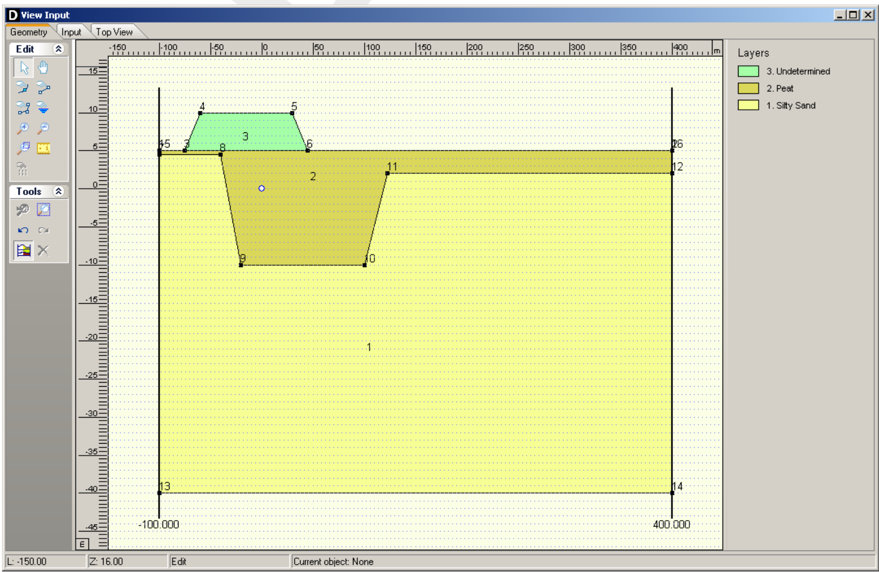


Figure 16.4: *View Input window, Geometry tab*

16.4 Soil layer properties

The settlement properties of the soil layers in the layered soil sequence should now be specified. The properties of the soil mass should be entered too.

18. Click *Soil* and select *Materials* on the menu bar to open the *Materials* window.
19. Select the soil name *Undetermined* in the left column of the *Materials* window and rename it with <Coarse Sand>. Enter the properties given in Figure 16.5.

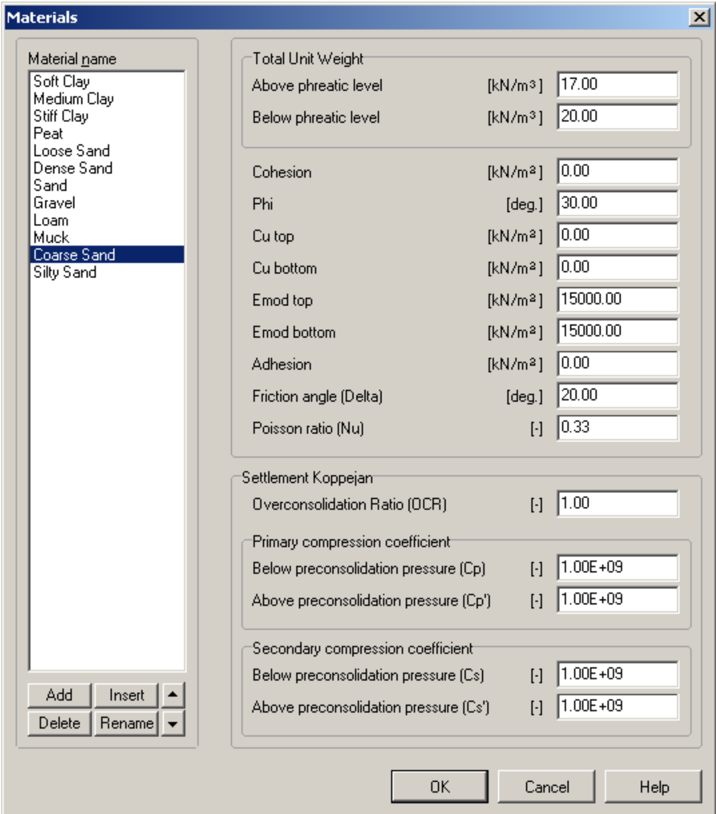


Figure 16.5: *Materials window*

20. Select the soil name *Silty Sand* and enter the *Settlement Koppejan* data given in Table 16.1.
21. Select the soil name *Peat* and enter the *Settlement Koppejan* data given in Table 16.1.
22. Finish the input of soil data by clicking *OK*.

16.5 Finishing the geometry of the longitudinal cross section

The defined soil properties have to be assigned to the drawn geometry of the longitudinal cross section (groundwater levels are assigned already). The assignments can be carried out by clicking geometry and choosing the subsequent described options on the menu bar.

23. Click *Geometry* and select *Layers* on the menu bar to open the *Layers* window to assign the soil properties to the soil layers in the longitudinal cross section.
24. Click on the tab *Materials*.
25. Assign the soil properties given in Figure 16.6.
26. Click *OK* to confirm the assignments.

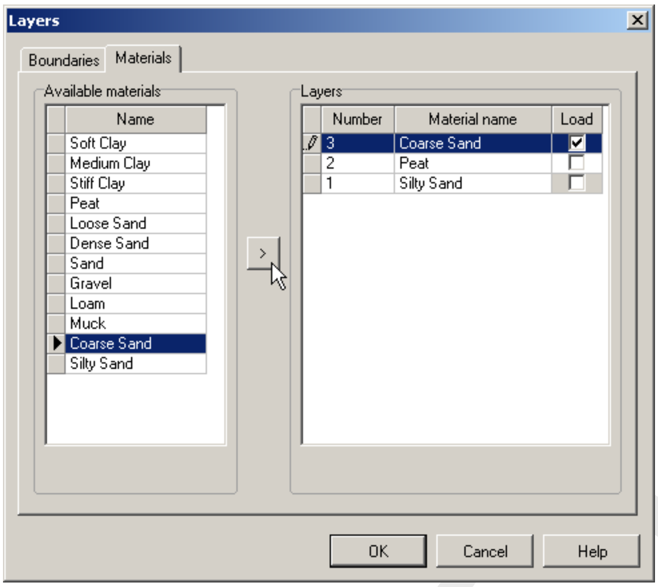


Figure 16.6: *Layers window, Materials tab*

16.6 Calculated soil mechanical parameters in export file

The calculation of the settlement of the soil layers below the pipeline is performed externally by D-SETTLEMENT (formerly known as MSettle), the settlement calculation program of the Deltares Systems tools. Therefore, the directory where the program is installed must be given:

27. Click *Tools* on the menu bar and select *Program Options* to open the *Program Options* window. Then select the *Locations* tab (Figure 16.7).
28. If needed, change the directory where the *Settlement program* is installed by clicking the *Browse* button.
29. Click *OK* to confirm.

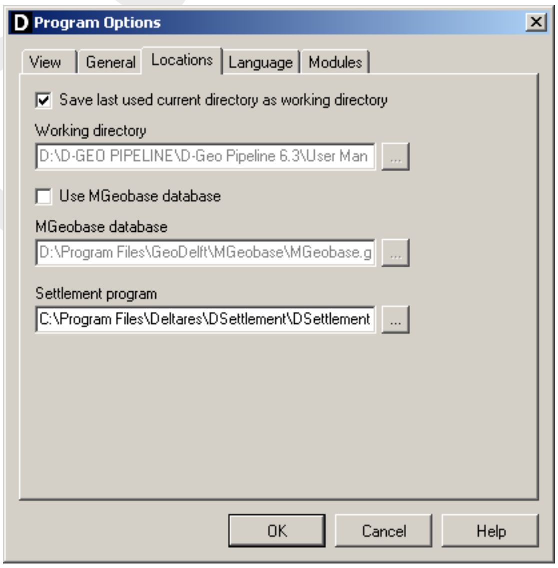


Figure 16.7: *Program Options window, Locations tab*

The other soil mechanical parameters are calculated automatically in D-GEO PIPELINE.

30. To start the calculations click *Calculation* and select *Start* on the menu bar to or press the function key F9. Ignore the message of Cu values of 0 above the drained undrained boundary.
31. Click *Results* and select *Report* on the menu bar to look at the results of the settlement calculation in paragraph 5.1 (Figure 16.8) and the calculation of the Soil Mechanical Parameters in paragraph 3.1 (Figure 16.9).

5 Deformations

5.1 Settlements of Soil Layers below the Pipeline

Vertical nr. [-]	Settlement [mm]	Additional settlement [mm]	dv [mm]
1	0	0	0
2	0	0	0
3	0	0	0
4	1910	0	1910
5	1891	0	1891
6	1864	0	1864
7	1192	0	1192
8	30	0	30
9	3	0	3
10	1	0	1
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0

Figure 16.8: *Report window, Settlements of soil layers below the pipeline*

3.1 Soil Mechanical Parameters

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m²
Pv;n	Neutral soil load	kN/m²
Ph;n	Neutral horizontal soil load	kN/m²
Pv,r;n	Reduced neutral soil load	kN/m²
kv,top1	Vertical modulus of subgrade reaction (bilinear) upward	kN/m³
kv,top2	Vertical modulus of subgrade reaction upward	kN/m³
dv	Vertical displacement	mm
kv	Vertical modulus of subgrade reaction downward	kN/m³
Pv;e	Vertical bearing capacity	kN/m²
kh	Horizontal modulus of subgrade reaction	kN/m³
Ph;e	Horizontal bearing capacity	kN/m²
tmax	Maximal friction along pipe	kN/m²
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m²]	Pv;n [kN/m²]	Ph;n [kN/m²]	Pv,r;n [kN/m²]	kv,top [kN/m³]
1	358	100	50	50	3982
2	807	185	93	70	3982
3	807	185	93	70	3982
4	189	87	65	76	457
5	189	87	65	76	457
6	189	87	65	76	457
7	87	30	23	27	457
8	8	2	2	2	457
9	8	2	2	2	457
10	8	2	2	2	457
11	215	61	30	38	3735
12	270	76	38	44	3884
13	270	76	38	44	3884
14	270	76	38	44	3884
15	270	76	38	44	3884
16	270	76	38	44	3884
17	270	76	38	44	3884
18	270	76	38	44	3884
19	270	76	38	44	3884
20	270	76	38	44	3884
21	270	76	38	44	3884
22	270	76	38	44	3884
23	270	76	38	44	3884
24	270	76	38	44	3884

Figure 16.9: *Report window, Soil Mechanical Parameters*

32. Click *File* and select *Export Results as csv. . .* on the menu bar to create an export file with the soil mechanical parameters.
33. Click on the *Save* button. The export file is saved on the same directory as Tutorial 9 and can be opened using the Excel program for example (see Figure 16.10).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1																												
2																												
3																												
4																												
5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
6	Header	Header	Header	Header	Bundle	Bundle	Bundle	Bundle	Bundle	Bundle	Bundle	Pipe	Pipe	Pipe	Pipe	Section	Section	Section	Section	Section	Section	Section	Section	Section	Section	Section	Section	Section
7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Axial	Axial	Axial	Axial	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Left	Left	Left	Left	Left
9	Company	Software	Date	Time	P1(x)	P1(y)	P1(z)	P2(x)	P2(y)	P2(z)	Length Pip	Pipe nr	Diameter T	Thickness T	Material T	Section nr	x	y	z	From	Curved	Delta	f	Qa	Qn	Qc	Qp	C1
10	[-]	[-]	[yyyy/mm/dd]	[hh:mm:ss]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	-	[mm]	[mm]	-	-	[m]	[m]	[m]	[m]	[boolean]	[m]	[-]	[kN/m2]	[kN/m2]	[kN/m2]	[kN/m2]	[kN/m3]
11		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	1	-80	0	-6	10	ToDoBool	0	0	0	10.04	0	1170.08	3007.83
12		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	2	-60	0	-6	30	ToDoBool	0	0	0	12.98	0	2344.86	3007.83
13		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	3	-40	0	-6	50	ToDoBool	0	0	0	12.98	0	2344.86	3007.83
14		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	4	-20	0	-6	70	ToDoBool	0	0	0	11.32	0	277.99	1378.2
15		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	5	0	0	-6	90	ToDoBool	0	0	0	11.32	0	277.99	1378.2
16		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	6	20	0	-6	110	ToDoBool	0	0	0	11.32	0	277.99	1378.2
17		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	7	40	0	-6	130	ToDoBool	0	0	0	5.78	0	108.03	1378.2
18		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	8	60	0	-6	150	ToDoBool	0	0	0	3.17	0	27.05	1378.2
19		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	9	80	0	-6	170	ToDoBool	0	0	0	3.17	0	27.05	1378.2
20		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	10	100	0	-6	190	ToDoBool	0	0	0	3.17	0	27.05	1378.2
21		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	11	120	0	-6	210	ToDoBool	0	0	0	8.48	0	726.55	2914.04
22		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	12	140	0	-6	230	ToDoBool	0	0	0	9.11	0	897.32	2952.28
23		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	13	160	0	-6	250	ToDoBool	0	0	0	9.11	0	897.32	2952.28
24		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	14	180	0	-6	270	ToDoBool	0	0	0	9.11	0	897.32	2952.28
25		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	15	200	0	-6	290	ToDoBool	0	0	0	9.11	0	897.32	2952.28
26		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	16	220	0	-6	310	ToDoBool	0	0	0	9.11	0	897.32	2952.28
27		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	17	240	0	-6	330	ToDoBool	0	0	0	9.11	0	897.32	2952.28
28		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	18	260	0	-6	350	ToDoBool	0	0	0	9.11	0	897.32	2952.28
29		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	19	280	0	-6	370	ToDoBool	0	0	0	9.11	0	897.32	2952.28
30		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	20	300	0	-6	390	ToDoBool	0	0	0	9.11	0	897.32	2952.28
31		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	21	320	0	-6	410	ToDoBool	0	0	0	9.11	0	897.32	2952.28
32		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	22	340	0	-6	430	ToDoBool	0	0	0	9.11	0	897.32	2952.28
33		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	23	360	0	-6	450	ToDoBool	0	0	0	9.11	0	897.32	2952.28
34		D-Geo Pipeline 6.3	26-7-2013	13:42:20	-80	0	-6	380	0	-6	12125.07	1	1200	22.4	Steel	24	380	0	-6	470	ToDoBool	0	0	0	9.11	0	897.32	2952.28

Figure 16.10: *Content of the CSV export file for Tutorial 9*

The export file contains the following data's:

◇ General data about the D-GEO PIPELINE project
◇ Pipeline data
◇ Horizontal soil mechanical data at the left and right of the pipe
◇ Vertical soil mechanical data at the top and bottom of the pipe

- ◇ Water data
- ◇ Axial soil data for friction

For more information, refer to section 3.1.2.

16.7 Conclusion

A pipe stress and settlement analysis has been performed for a polyethylene pipe in a layered soil. The inputs and results of this calculation have been exported in a csv file in order to perform an extended stress analysis using an other program.

17 Tutorial 10: Subsidence after micro tunneling

This tutorial provides some detail on subsidence calculations in D-GEO PIPELINE. Subsidence is related to surface level changes due to excavation of the subsurface by the micro tunneling machine.

The objectives of the exercise are:

- ◇ To enter a non linear bore path;
- ◇ To evaluate the subsidence along the pipeline.

The following modules are needed:

- ◇ D-GEO PIPELINE Standard module (HDD)
- ◇ Micro Tunneling module

This tutorial is presented in the file Tutorial-10.dri.

17.1 Introduction to the case

17.1.1 Volume loss along the tunnel excavation

Subsidence is related to the volume loss along the tunnel excavation, e.g. the excess soil removed by the Micro Tunneling Boring Machine (MTBM). The subsidence mechanism is described in detail in section 26.3.

To reduce the friction between pipe and wall of the drilling hole, and allow the optional use of friction reducing fluids, the drilling diameter (R) is usually somewhat larger then the pipe diameter (r).

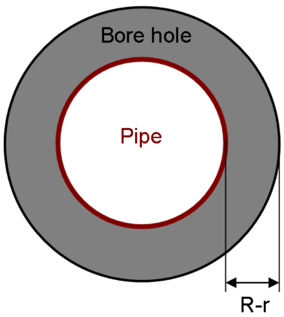


Figure 17.1: *Bore hole section*

The space created between pipe and wall is called overcut: the distance $R - r$. See section 4.6.2.2 for entering the overcut. The overcut is generally filled by lubrication fluid depending on the type of lubrication fluid the amount of filling may reduce during or after installation:

- ◇ Part of the soil above subsides during operation
- ◇ Compaction/consolidation of the lubrication fluid after installation

The volume loss as percentage of the overcut area is defined as.

$$V_s = \upsilon \, \pi \left(R^2 - r^2\right) \tag{17.1}$$

Note: If one wants to model subsidence due to drilling with a low face support pressure or to model the influence of densification of granular soils this value may be set above 100%.

The volume loss causing subsidence is in D-GEO PIPELINE based on the expected overcut of the soil.

$$V_{\text{s}} = \frac{\upsilon\,\pi}{4}\left((D_{\text{o}} + 2\,l_{\text{overcut}})^2 - D_{\text{o}}^2\right) \tag{17.2}$$

where:

υ	is the percentage volume loss, in %;
V_{S}	is the differential volume, in m^3/m;
D_{o}	is the pipe diameter, in m;
l_{overcut}	is the overcut on radius, in m.

The volume created by the over cut is initially filled with lubrication fluid. Within a time period the lubrication fluid will consolidate and the overburden will subside into space created by consolidation. The subsidence w at the surface is calculated as follows:

$$w = \frac{V_{\text{s}}}{\sqrt{2\pi i^2}} \exp\left(-\frac{r^2}{2i^2}\right), \qquad z < z_0 \tag{17.3}$$

where:

i	is the distance in between the center of the tunnel or pipeline and the inflection point of the trough, in m;
z_0	is the depth of the center of the pipeline or tunnel, in m;
z	is the depth at which the settlement is calculated, in m;
V_{S}	is the differential volume, in m^3/m.

For detail on the shape factor i, see section 26.3.

17.1.2 Modification of the drilling line

A vertical and a horizontal bending radius in the design drilling line for micro tunneling is a possibility. In this tutorial the drilling line is modified in order to avoid drilling through the peat layer.

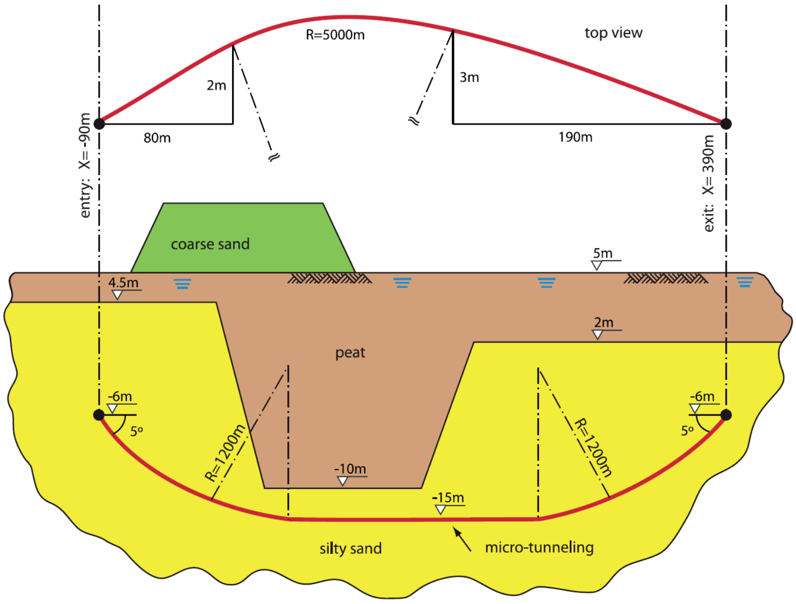


Figure 17.2: *Pipeline configuration of Tutorial 10*

Often the horizontal bend is part of one of the vertical bending radii. In case the horizontal bending radius coincides with part of a vertical bending radius, a combined 3-dimensional bending radius is formed. For the design of the horizontal directional drilling line, the pull back force and the strength calculation it is necessary to determine the value of the 3 dimensional bending radius.

The value of the three dimensional bending radius can be calculated as follows:

$$R_{\text{combi}} = \sqrt{\frac{R_{\text{h}}^2 \times R_{\text{v}}^2}{R_{\text{h}}^2 + R_{\text{v}}^2}} \tag{17.4}$$

where:

R_{combi}	is the combined bending radius, in m;
R_{h}	is the horizontal bending radius, in m;
R_{v}	is the vertical bending radius, in m.

As has to be mentioned that the current version of D-GEO PIPELINE does not take the soil reaction forces into account in the curve. Therefore the effect on the friction caused by soil reaction effects in curves is not considered in D-GEO PIPELINE.

This tutorial is based on continuation of the file used in Tutorial 9 (chapter 16).

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select <Tutorial-9> and click the *Open* button to open de file.
3. Click *File* and select *Save As* on the menu bar to open the *Save As* window and rename the file into <Tutorial-10>.
4. Click the *Save* button to save the file for Tutorial 10.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.

6. Fill in <Tutorial 10 for D-GEO PIPELINE > and <Subsidence after micro tunneling> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.
8. In the *Model* window from the *Project* menu, unselect the option *Use settlement*.
9. Click *OK*.

17.2 Pipeline Configuration

The horizontal and vertical curves must be specified in the pipeline configuration window.

10. Click *Pipe* and select *Pipeline Configuration* on the menu bar to open the *Pipeline Configuration* window.
11. Enter the values given in Figure 17.3.
12. Click *OK* to confirm.

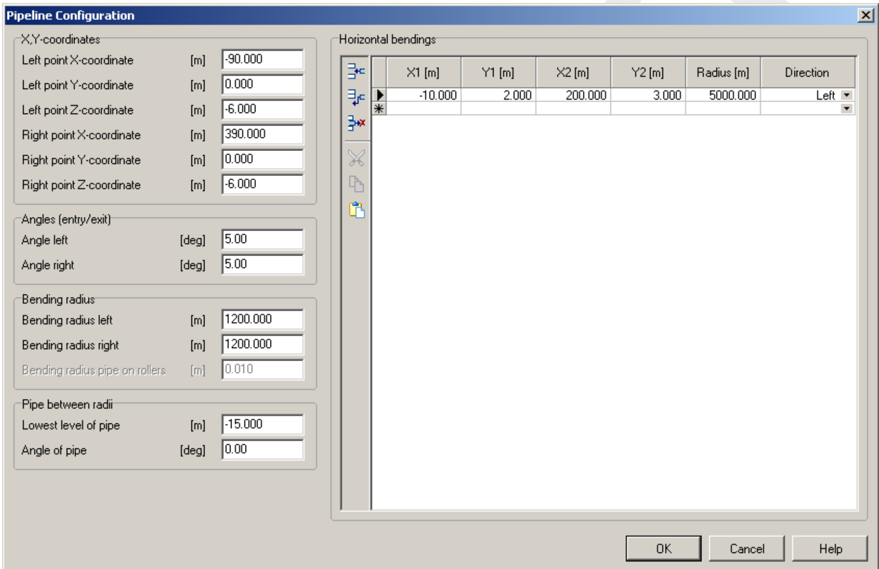


Figure 17.3: *Pipeline Configuration window*

13. Look at the entered horizontal bending on the *Top View* tab of the *View Input* window (Figure 17.4).
14. Look at the longitudinal cross section on the *Input* tab of the *View Input* window and notice the elongation of the longitudinal cross section. Therefore it is recommended to check, in case of projects with changing 3D pipeline configurations, if the soil layer sequence in the longitudinal cross section is still reliable (according to the soil investigation data).

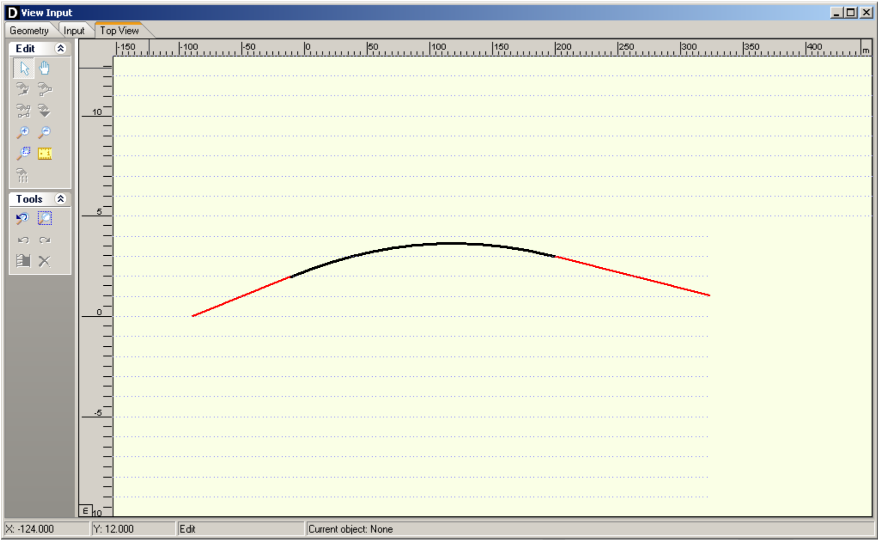


Figure 17.4: *View Input window, Top View tab*

Note: The horizontal bending is indicated with a black bold line in the top view (Figure 17.4).

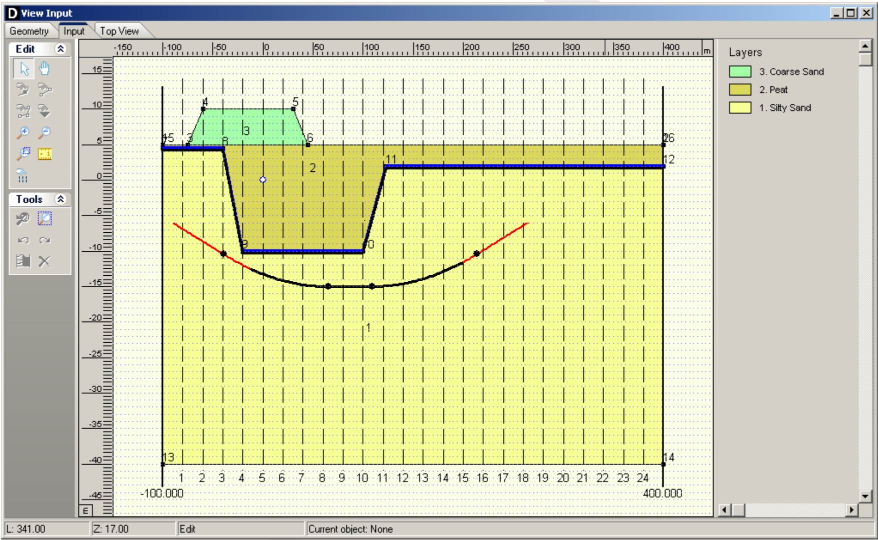


Figure 17.5: *View Input window, Input tab*

17.3 Material data

After the input of the drilling line, the pipe material is chosen.

15. Click *Pipe* from the menu and select *Product Pipe Material Data* to open the *Product Pipe Material Data* window.
16. Enter the values as presented in Figure 17.6.

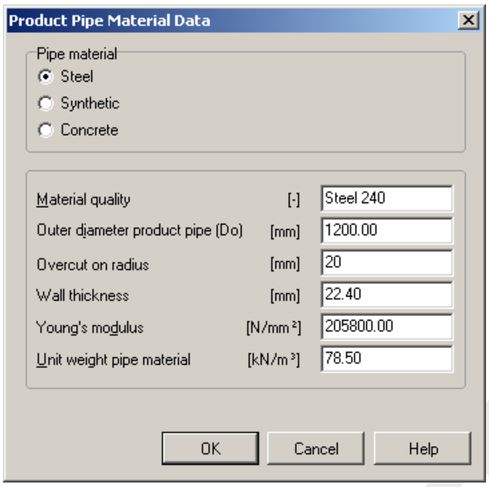


Figure 17.6: *Product Pipe Material Data window*

The overcut on the radius amounts to 20 mm, which equals 40 mm on the diameter of the pipeline.

17.4 Engineering Data

The percentage of volume loss is specified in the *Engineering Data* window. In this tutorial a value of 110 % is chosen, so that the effect of drilling with a relative low face pressure (lower than the neutral face pressure) is incorporated.

17. Select *Engineering Data* from the *Pipe* menu bar to open the *Engineering Data* window.
18. Enter the values as given in Figure 17.7.

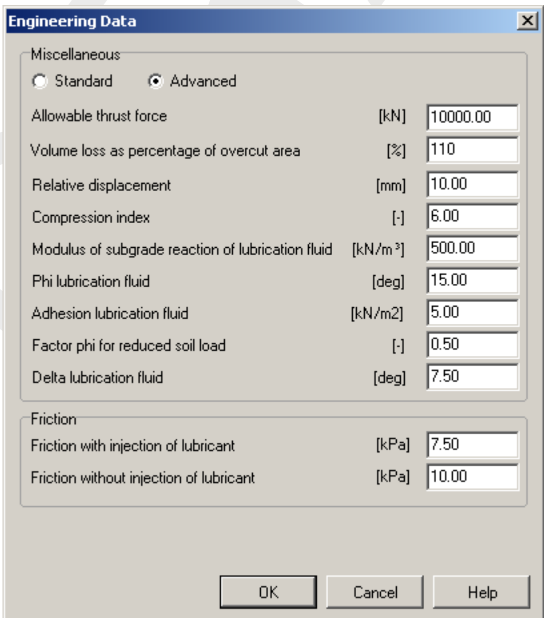


Figure 17.7: *Engineering Data window*

17.5 Results: Subsidence

To view the calculation results for the subsidence trough as apparent at surface:

19. To start the calculations click *Calculation* and select *Start*on the menu bar or press the function key F9.
20. Click *Results* and select *Subsidence Profiles* from the menu bar to open the *Subsidence Profiles* window (Figure 17.8).
21. Check the box labeled “Fix axis”, click on the vertical number edit box. Now move through the verticals by using the up/down arrows on the key board.

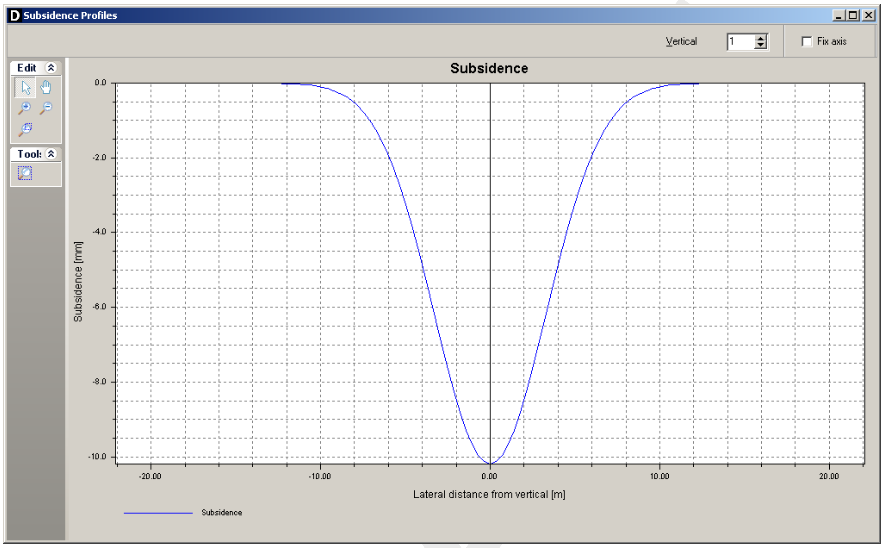


Figure 17.8: *Subsidence Profiles window for vertical 1*

18 Tutorial 11: Installation of pipeline in a trench

This tutorial considers installation of a concrete sewer by means of trenching. A trench is made by excavation, the pipe is installed, and the trench is often filled with the soil derived from the excavation itself. The risks involved during installation include slope failure and bursting of the trench bottom. After installation uplift of the pipe and pipe deformation due to settlement are problems that may occur.

The objectives of the exercise are:

◇ To schematize the soil layers with groundwater with different hydraulic heads;
◇ To calculate the soil mechanical parameters for a pipeline in a trench.

The following modules are needed:

◇ D-GEO PIPELINE Standard module (HDD)
◇ Trenching module

This tutorial is presented in the file Tutorial-11.dri.

18.1 Introduction to the case

In this tutorial a simple trench is modeled. The trench passes a small waterway. The geometry of tutorial 7 forms the base of this tutorial.

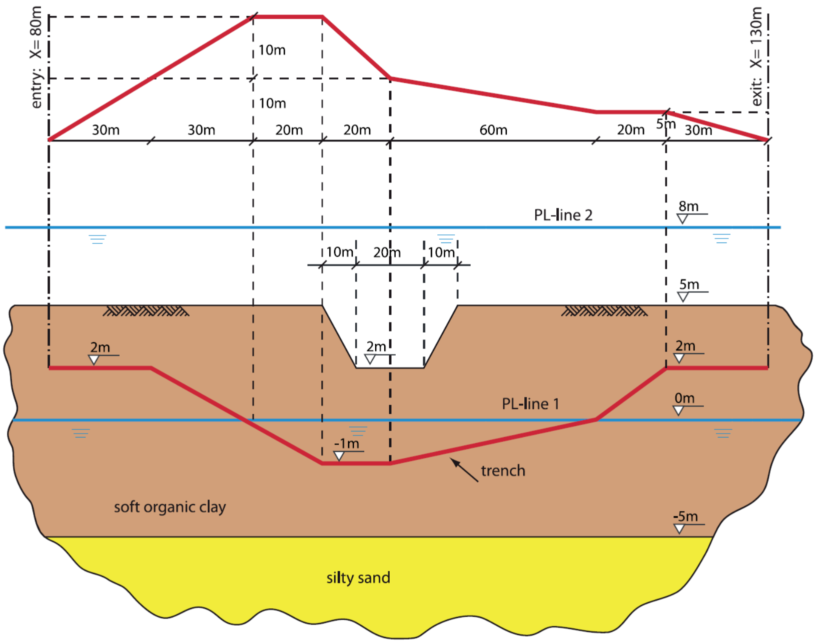


Figure 18.1: *Geometry of Tutorial 11*

This tutorial is based on continuation of the file used in Tutorial 7 (chapter 14).

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select *Tutorial-7* and click the *Open* button to open de file.
3. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-11>.

Table 18.1: *Layer properties (Tutorial 11)*

		Silty Sand	**Soft Organic Clay**
Dry unit weight	[kN/m^3]	18	13
Wet unit weight	[kN/m^3]	20	13
Cohesion	[kN/m^2]	0	2
Angle of internal friction	[°]	10	18
Undrained strength top	[kN/m^2]	0	10
Undrained strength bottom	[kN/m^2]	0	30
E modulus top	[kN/m^2]	10000	500
E modulus bottom	[kN/m^2]	15000	1000
Adhesion	[kN/m^2]	0	2
Friction angle	[0]	20	9
Poisson's ratio	[-]	0.35	0.45

4. Click the *Save* button to save the file for Tutorial 11.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 11 for D-GEO PIPELINE > and <Installation of pipeline in a trench> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

18.2 Model

Since this tutorial considers an installation of the pipeline in a trench the model trench should be selected.

8. On the menu bar, click *Project* and then choose *Model* to open the *Model* window.
9. Select *Construction in trench*, and click *OK*.

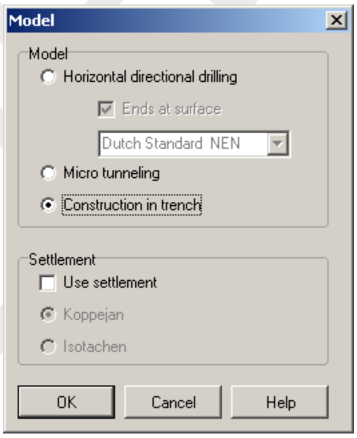


Figure 18.2: *Model window*

18.3 Geometry of the longitudinal cross section

This tutorial considers a layered soil sequence. The typical Dutch soil sequence of a soft organic clay layer on top of a coarse sand layer will be considered. The organic clay layer is compressible and exhibits a low permeability, while the sand layer is assumed incompressible and exhibits a high permeability. The new soil layers should be specified in the geometry window.

10. In the *View Input* window, switch to the *Geometry* tab to edit the existing soil layer sequence.
11. Click the *Add single line* icon from the *Edit* sub-window to draw an additional top line of a soil and position the straight line at Z = -5 m.
12. Click the *Automatic regeneration of geometry on/off* icon from the *Tools* sub-window so that the geometry as shown in Figure 18.3 appears. If the *Automatic regeneration of geometry* icon is already selected, click on the *Edit* icon to regenerate the geometry.
13. Click the *Add pl-line(s)* icon from the *Edit* sub-window and position the level of the artesian groundwater at coordinate Z = 8 m. The blue dashed line, which appears in the longitudinal cross section, represents the second groundwater line (PL line 2). This second groundwater line will be used in section 18.5.3 to specify the water pressure distribution in the sand aquifer.

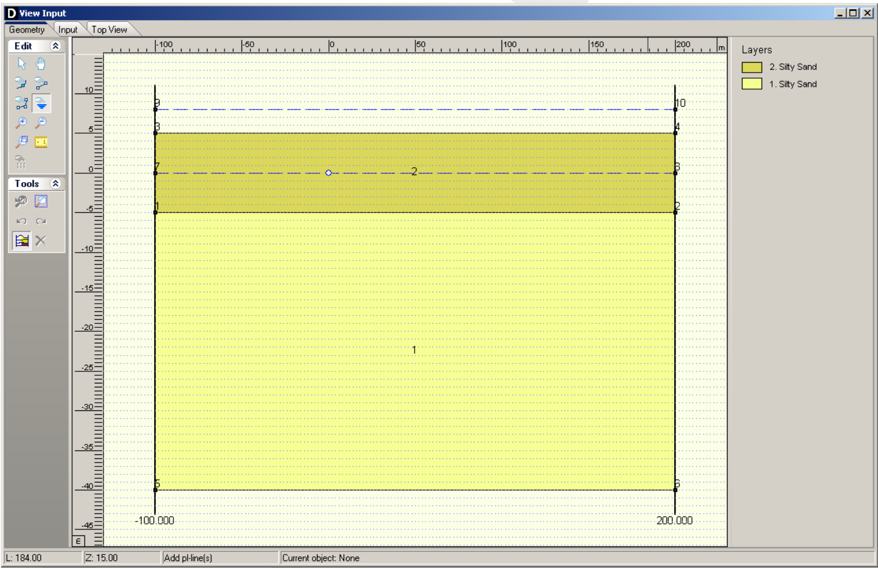


Figure 18.3: *View Input window, Geometry tab*

18.4 Soil layer properties

The properties of the soil layers in the layered soil sequence should now be specified.

14. Click *Soil* and select *Materials* on the menu bar to enter the soil data.
15. Add a new material by choosing the *Add* button Add below the materials list on the left side of the window. Enter the soil material name <Soft Organic Clay>.
16. Enter the soil data given in Table 18.1.
17. Finish the input of soil data by clicking *OK*.

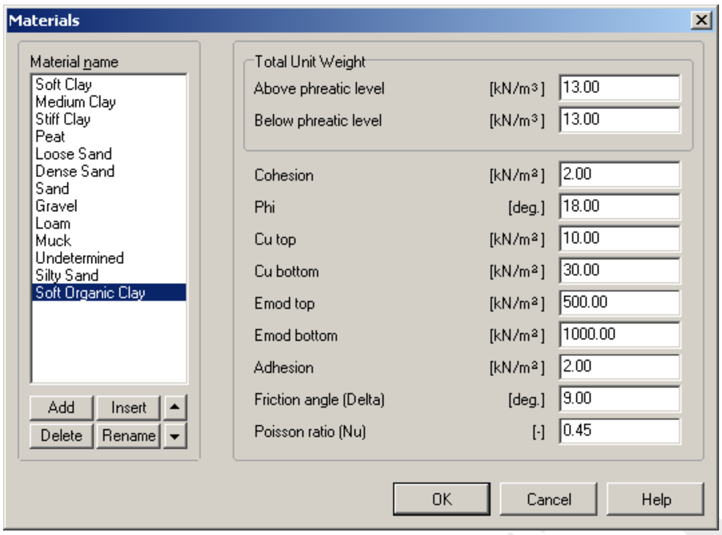


Figure 18.4: *Materials window*

18.5 Finishing the geometry of the longitudinal cross section

The defined soil properties and the groundwater levels have to be assigned to the drawn geometry of the longitudinal cross section. The assignments can be carried out in the *Geometry* menu.

18.5.1 Phreatic Line

18. Click *Geometry* and select *Phreatic Line* on the menu bar to open the *Phreatic Line* window (Figure 18.5) and select PL-line <1> as phreatic line for calculation of the groundwater pressures.
19. Click *OK*.

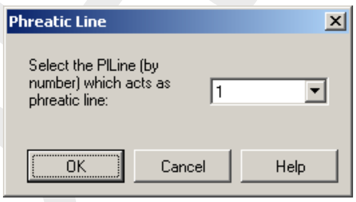


Figure 18.5: *Phreatic Line window*

18.5.2 Layers

20. Click *Geometry* and select *Layers* on the menu bar to open the *Layers* window. Select the *Materials* tab to assign the soil properties to the soil layers in the longitudinal cross section.
21. Assign the properties of the defined layer *Soft Organic Clay* to layer number 2 in the longitudinal cross section. The defined properties of *Soft Organic Clay* are assigned to layer *Number 2* by clicking the *Assign* icon in between the left and the right column (Figure 18.6).

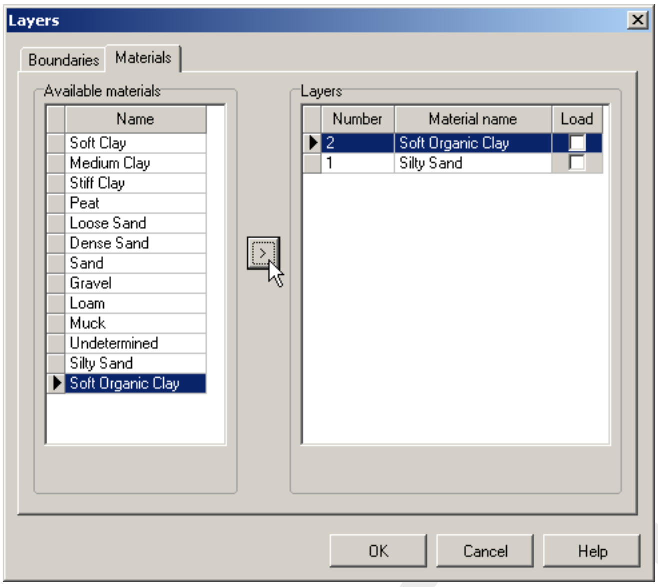


Figure 18.6: *Layers window, Materials tab*

22. Click on the *OK* button to quit the window and return to the *Geometry* tab of the *View Input* window to look at the change of layers name in the legend (Figure 18.7).

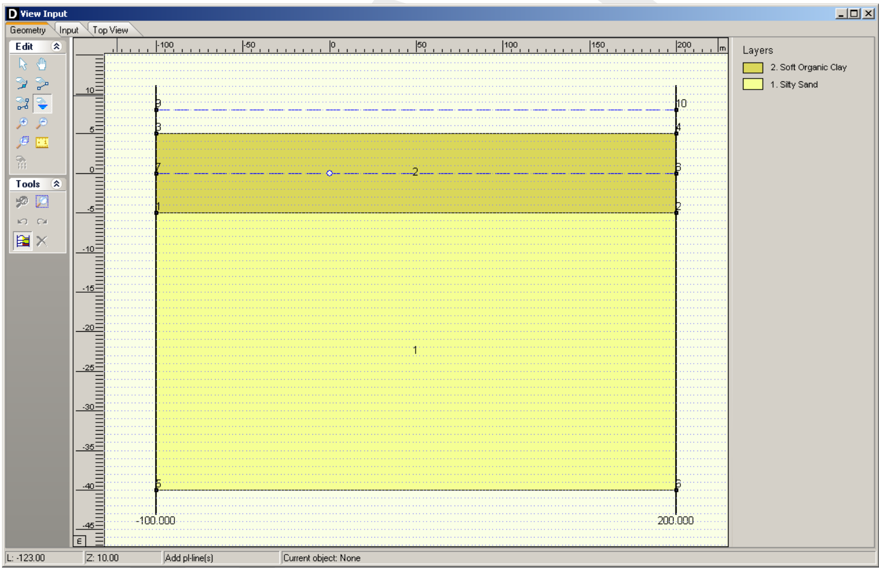


Figure 18.7: *View Input window, Geometry tab*

18.5.3 PL-Lines per Layer

23. Click *Geometry* and select *Pl-lines per Layers* on the menu bar to open the *PL-lines per Layer* window to assign the defined PL–lines to the soil layers in the longitudinal cross section. Those information's are used for the calculation of the groundwater pressure distribution.
24. The groundwater pressure at the top of the *Soft Organic Clay* layer should be calculated based on the hydraulic head of PL–line 1, the phreatic line (Figure 18.5). Since the *Coarse Sand* layer is an aquifer with an enhanced artesian groundwater pressure, the groundwater pressure at the bottom of the clay layer should be calculated based on the hydraulic head of PL–line 2. Of course the water pressure at the top and at the bottom of the coarse sand layer should be calculated based on the hydraulic head of PL–line 2. This will result in the

Pl-lines per layer window shown in Figure 18.8.

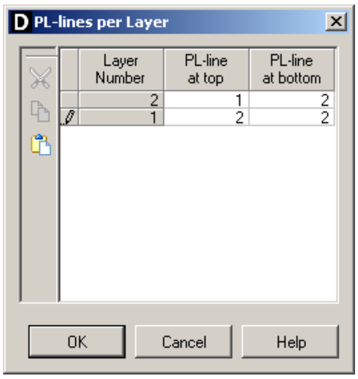


Figure 18.8: *PL-lines per Layer window*

25. Click *OK* to confirm.
26. The geometry can be tested by clicking *Geometry* on the menu bar and selecting *Check Geometry*. If the geometry is entered properly, the message *Geometry has been tested and is OK* appears.
27. Click *OK* to close this window.

18.6 Adding a waterway

A small waterway will now be drawn in the geometry.

28. Select the *Geometry* tab and select the *Add poly line(s)* button .
29. Draw a profile line as in Figure 18.9a. Remove points that are not required by clicking the right mouse button and selecting the option *Delete All Loose Lines*.
30. Select the top line (between points 3 and 6 as shown in Figure 18.9b.
31. Click the *Delete* button . This should result in Figure 18.9c.

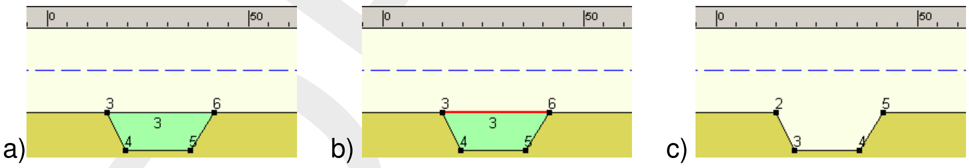


Figure 18.9: *View Input window, Geometry tab (steps for drawing a waterway)*

Now give the exact location of the waterway:

32. Check and enter the exact coordinates of the points by opening the *Points* window from the *Geometry* menu.
33. Enter correct values for points 2, 3, 4 and 5 as shown in Figure 18.10.

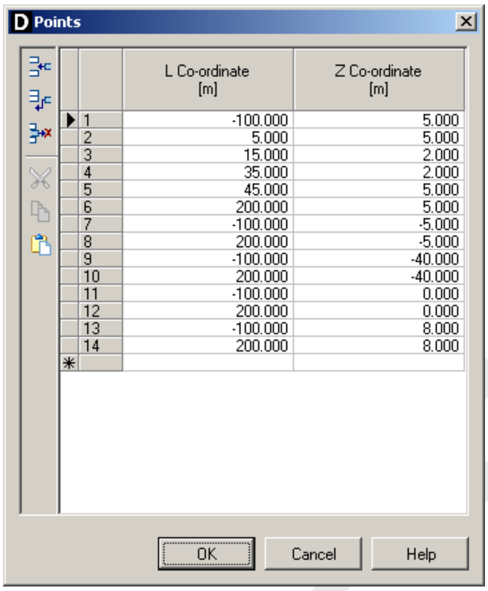


Figure 18.10: *Points window*

18.7 Calculation Verticals

In the subsequent table the verticals for the location of the calculations are given.

34. Open the *Calculation Verticals* window.
35. Enter <-70> and <130> for the *First* and *Last L* values and an *Interval* of <20>.
36. Click the *Generate* button.

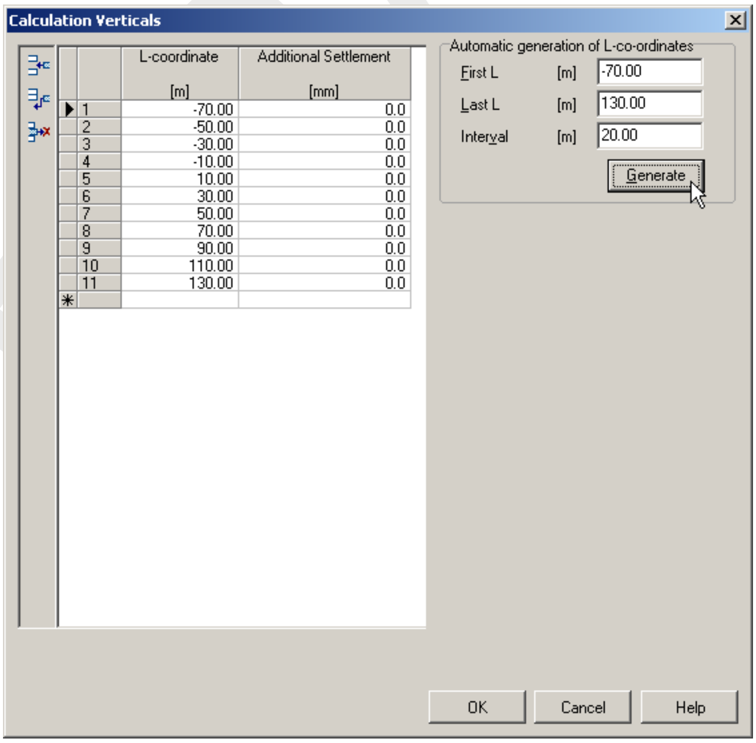


Figure 18.11: *Calculation Verticals window*

18.8 Boundaries Selection

To indicate the boundary compressible/uncompressible layers and impermeable/permeable layers, the top of a specific layer is used. In this case it is evident that this is the top of the coarse sand layer.

37. From the main menu click *GeoObjects* and select *Boundaries Selection*.
38. Select *Top of layer* <1> as both boundaries.
39. Click OK.

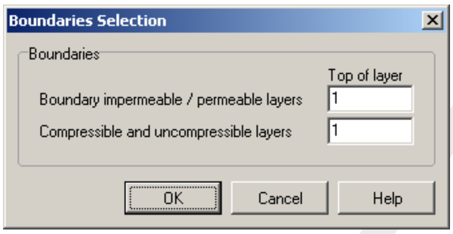
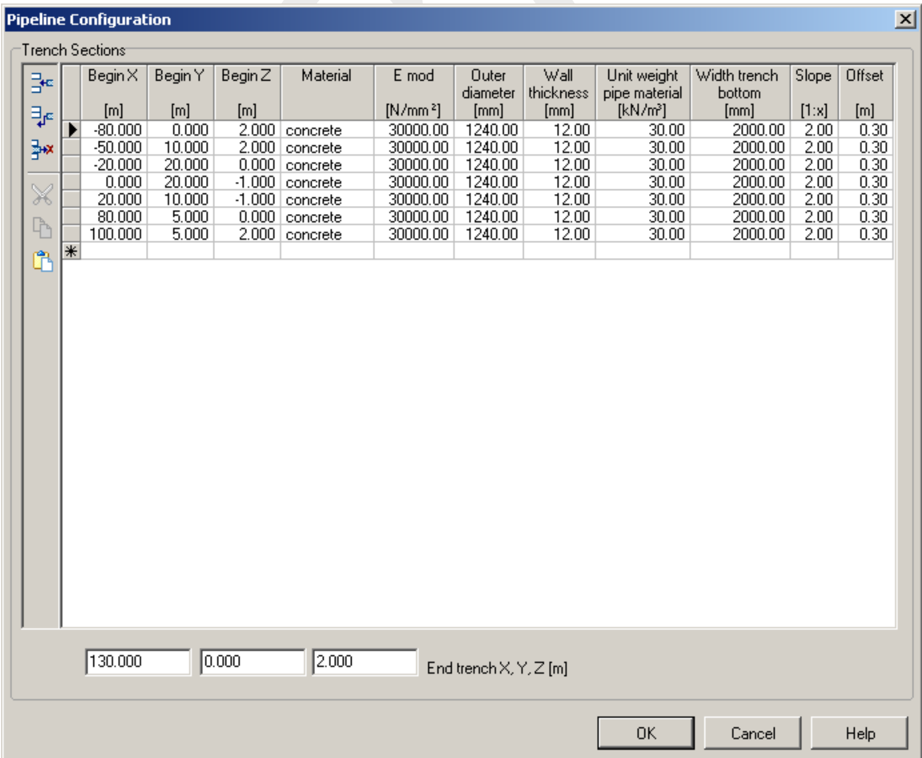


Figure 18.12: *Boundaries Selection window*

18.9 Trench configuration and pipe material

As the trench passes a small waterway, for practical reasons it has to subduct. An initial distance of about 1.5 meter is chosen between trench and bottom waterway.

40. Click *Pipe* and select *Pipeline Configuration* from the menu bar to open the *Pipeline Configuration* window.
41. Enter the values as presented in Figure 18.13.
42. Click *OK* to accept the entries.



Begin X [m]	Begin Y [m]	Begin Z [m]	Material	E mod [N/mm²]	Outer diameter [mm]	Wall thickness [mm]	Unit weight pipe material [kN/m³]	Width trench bottom [mm]	Slope [1:x]	Offset [m]
-80.000	0.000	2.000	concrete	30000.00	1240.00	12.00	30.00	2000.00	2.00	0.30
-50.000	10.000	2.000	concrete	30000.00	1240.00	12.00	30.00	2000.00	2.00	0.30
-20.000	20.000	0.000	concrete	30000.00	1240.00	12.00	30.00	2000.00	2.00	0.30
0.000	20.000	-1.000	concrete	30000.00	1240.00	12.00	30.00	2000.00	2.00	0.30
20.000	10.000	-1.000	concrete	30000.00	1240.00	12.00	30.00	2000.00	2.00	0.30
80.000	5.000	0.000	concrete	30000.00	1240.00	12.00	30.00	2000.00	2.00	0.30
100.000	5.000	2.000	concrete	30000.00	1240.00	12.00	30.00	2000.00	2.00	0.30

Figure 18.13: *Pipeline Configuration window*

43. Now examine the trench trajectory in the *Input* (Figure 18.14) and *Top View* (Figure 18.15) tabs of the *View Input* window.

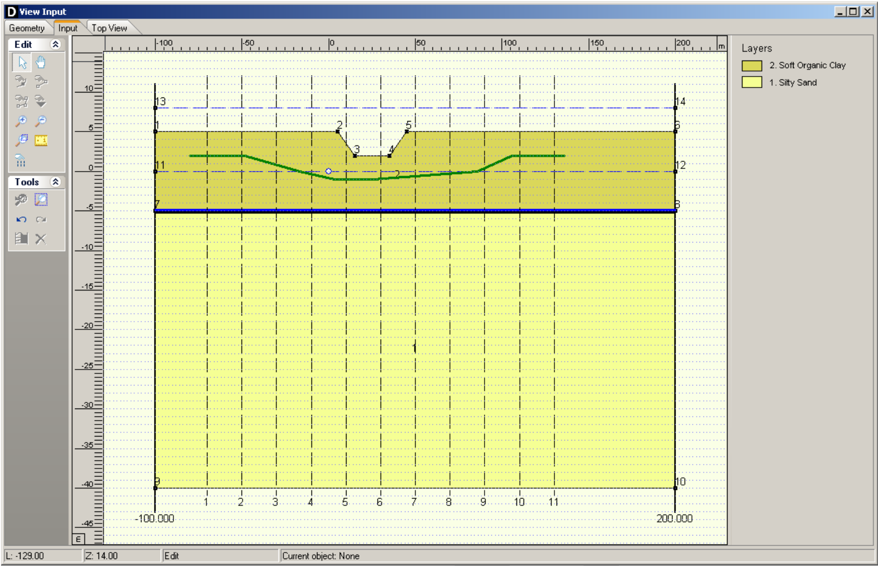


Figure 18.14: *View Input window, Input tab*

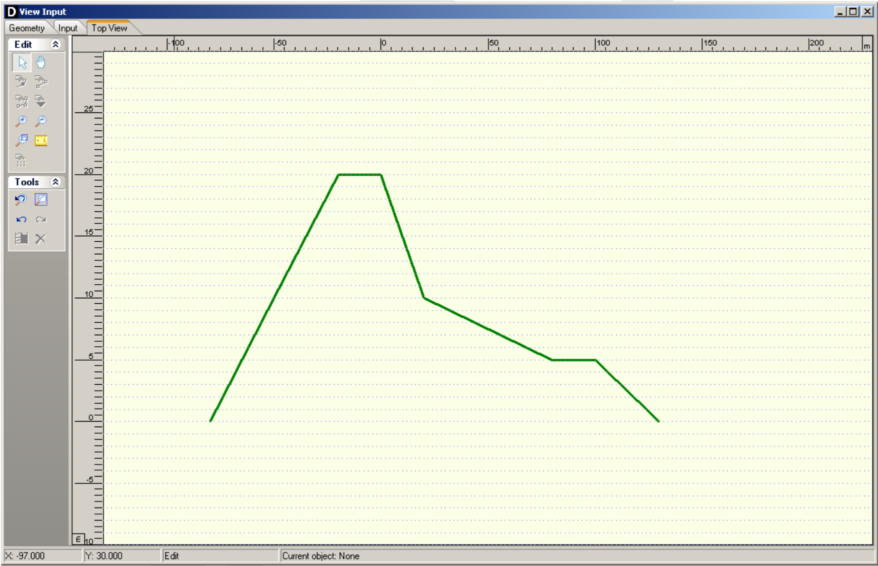


Figure 18.15: *View Input window, Top View tab*

18.10 Engineering Data

Next the engineering data is added. The trench is excavated in organic clay, and filled with the excavated material, the fill is poorly compacted.

44. Click *Pipe* from the menu bar and select *Engineering Data* to open the *Engineering Data* window.
45. Select <Soft Soils> as *Type of fill* and <Poorly compacted> as *Compaction of fill*.
46. Click *OK* to confirm.

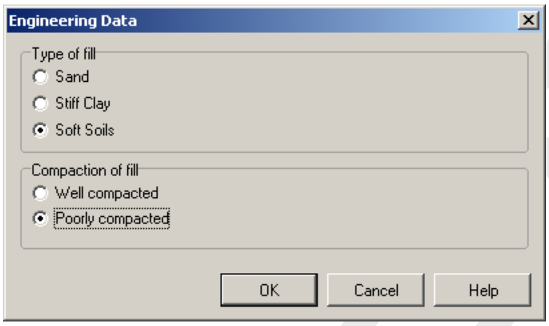


Figure 18.16: *Engineering Data window*

18.11 Results: Soil Mechanical Parameters

47. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.
48. Open the *Report* window from the *Results* menu to view the results of the *Soil Mechanical Parameters*. The results can be found in paragraph 3.1 (Figure 18.17).

Since the fill of the trench is assigned the property "poorly compacted" a relatively high initial soil load on the pipe is expected.

3.1 Soil Mechanical Parameters

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m^2
Pv;n	Neutral soil load	kN/m^2
Ph;n	Neutral horizontal soil load	kN/m^2
Pv;a	Actual soil load	kN/m^2
kv,top1	Vertical modulus of subgrade reaction (bilinear) upward	kN/m^3
kv,top2	Vertical modulus of subgrade reaction upward	kN/m^3
dv	Vertical displacement	mm
kv1	Vertical modulus of subgrade reaction downward, first branch	kN/m^3
kv2	Vertical modulus of subgrade reaction downward, second branch	kN/m^3
Pv;e	Vertical bearing capacity	kN/m^2
kh	Horizontal modulus of subgrade reaction	kN/m^3
Ph;e	Horizontal bearing capacity	kN/m^2
tmax	Maximal friction along pipe	kN/m^2
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m^2]	Pv;n [kN/m^2]	Ph;n [kN/m^2]	Pv;a [kN/m^2]	kv,top1 [kN/m^3]	kv,top2 [kN/m^3]
1	50	33	23	41	33	94
2	50	33	23	41	33	94
3	87	48	33	71	97	215
4	133	63	44	110	214	407
5	77	39	27	62	105	211
6	33	20	14	26	24	64
7	141	64	44	117	248	451
8	130	62	43	108	205	392
9	102	53	37	84	132	274
10	50	33	23	41	33	94
11	50	33	23	41	33	94

Vertical nr.	dv [mm]	kv1 [kN/m^3]	kv2 [kN/m^3]	Pv;e [kN/m^2]	kh [kN/m^3]	Ph;e [kN/m^2]	tmax [kN/m^2]	dmax [mm]	mat [-]
1	n.a.	1566	251	331	3632	121	7	8	Clay
2	n.a.	1566	251	331	3632	121	7	8	Clay
3	n.a.	1904	305	447	4390	176	9	8	Clay
4	n.a.	1800	288	487	4403	207	9	8	Clay
5	n.a.	798	128	279	2673	112	5	8	Clay
6	n.a.	396	63	141	1518	50	3	8	Clay
7	n.a.	1660	266	463	4088	198	8	8	Clay
8	n.a.	1843	295	494	4498	209	9	8	Clay
9	n.a.	1930	309	476	4623	197	9	8	Clay
10	n.a.	1566	251	331	3632	121	7	8	Clay
11	n.a.	1566	251	331	3632	121	7	8	Clay

Figure 18.17: *Report window, Soil Mechanical Parameters section*

The initial soil load Pv;a may be reduced by changing the fill property to “well compacted” (see Equation 23.9 in section 23.4). Note that in reality this requires an extra compaction treatment after installation of the pipe. In the software this can be adjusted in the *Engineering Data* window under the *Pipe* menu.

19 Tutorial 12: Trenching: uplift and heave

This tutorial is the continuation of tutorial 11 (chapter 18) and considers installation of a concrete sewer by means of trenching.

The objectives of the exercise are:

- ◇ To evaluate the risk on heave of the bottom of the trench during installation;
- ◇ To evaluate possible uplift of the empty pipe after installation.

The following modules are needed:

- ◇ D-GEO PIPELINE Standard module (HDD)
- ◇ Trenching module

This tutorial is presented in the files Tutorial-12a.dri, Tutorial-12b.dri and Tutorial-12c.dri.

19.1 Introduction to the case

During the excavation of a trench the groundwater conditions may play an important role. In case a trench is excavated below the phreatic groundwater table or in case the hydraulic head of an aquifer is relatively high, heave of the bottom of the trench is a serious risk. An other risk, which may occur after excavation of the trench below the phreatic groundwater table, is the uplift due to fill with a low density soil.

In this tutorial, the top layer consists of peat instead of organic clay. The peat exhibits a low density. Besides a low density top layer, this tutorial considers a situation with a phreatic groundwater table at the surface level.

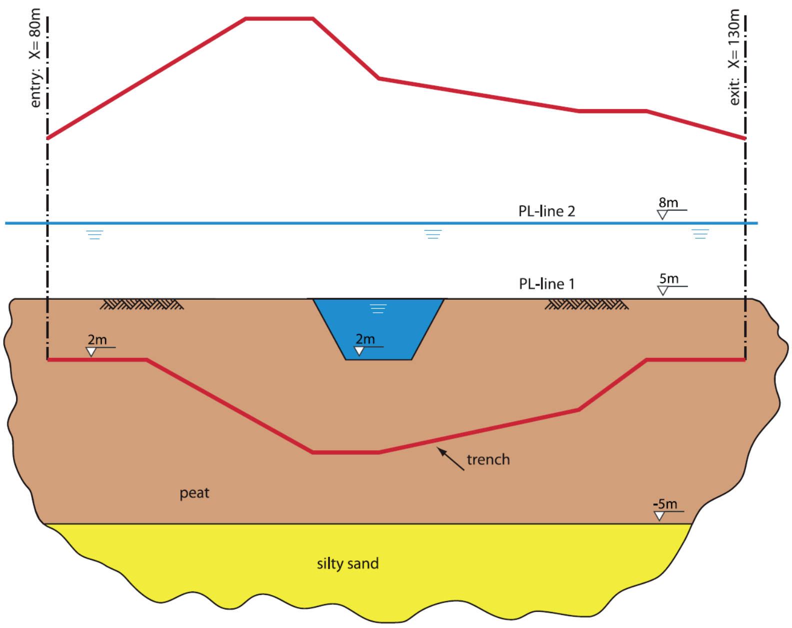


Figure 19.1: *Pipeline configuration for Tutorial 12*

Table 19.1: *Layer properties (Tutorial 12)*

		Silty Sand	**Peat**	**Soft Organic Clay**
Dry unit weight	[kN/m^3]	18	10.2	13
Wet unit weight	[kN/m^3]	20	10.2	13
Cohesion	[kN/m^2]	0	2	2
Angle of internal friction	[°]	10	15	18
Undrained strength top	[kN/m^2]	0	10	10
Undrained strength bottom	[kN/m^2]	0	20	30
E modulus top	[kN/m^2]	10000	1000	500
E modulus bottom	[kN/m^2]	15000	1500	1000
Adhesion	[kN/m^2]	0	2	2
Friction angle	[°]	20	5	9
Poisson's ratio	[-]	0.35	0.45	0.45

This tutorial is based on continuation of the file used in Tutorial 11 (chapter 18).

1. Click *File* and select *Open* on the menu bar, and select Tutorial-11.
2. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-12a>.
3. Click the *Save* button to save the file for Tutorial 12a.
4. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
5. Fill in <Tutorial 12 for D-GEO PIPELINE > and <Trenching: uplift and heave> for *Title 1* and *Title 2* respectively in the *Identification* tab.

19.2 Materials

The soil investigation showed presence of peat layers instead of organic clay. First, peat is added to the material list.

6. Click *Soil* and select *Materials* on the menu bar to open the *Materials* window.
7. Select the existing *Peat* material in the left side of the window and enter the values as given in Table 19.1.
8. Click *OK*.

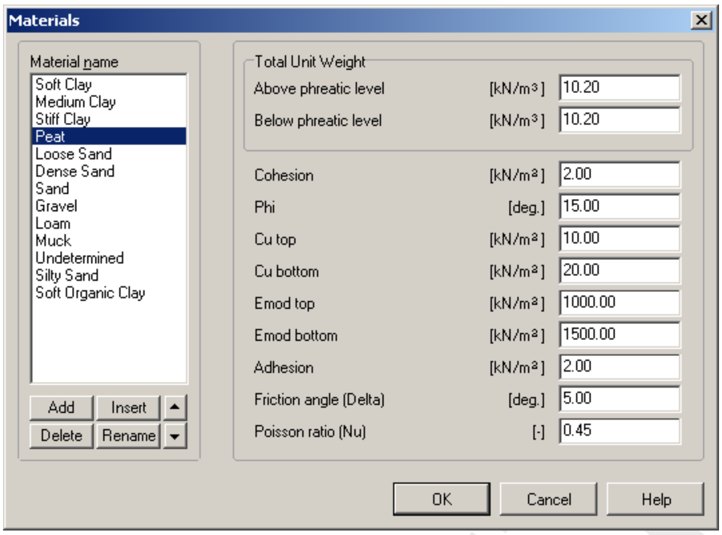


Figure 19.2: *Materials window*

Assign this material type to the top layer:

9. Click *Geometry* and select *Layers* on the menu bar.
10. To assign a material to a layer, select the *Material* tab. Select <Peat> as well as layer number <2> and via the arrow button assign the soil to the layer (Figure 19.3).
11. Accept the input and return to the main window by clicking *OK*.

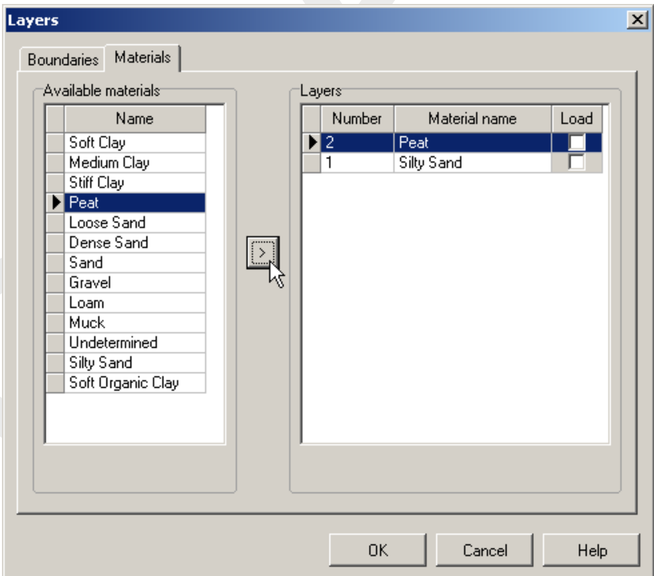


Figure 19.3: *Layers window, Materials tab*

19.3 Phreatic level

The phreatic line (groundwater table) is located at the surface level in this tutorial.

12. In the *Geometry* tab of the *View Input* window, select the *Edit* button and click on the PL line 1 in order to select the phreatic line by choosing *Select PL Line 1*.
13. Once the PL line 1 has been selected, drag it to the surface level by pressing and holding down the left-hand mouse button while relocating the mouse cursor.

14. Check and possibly correct the level of the line as shown in Figure 19.4.

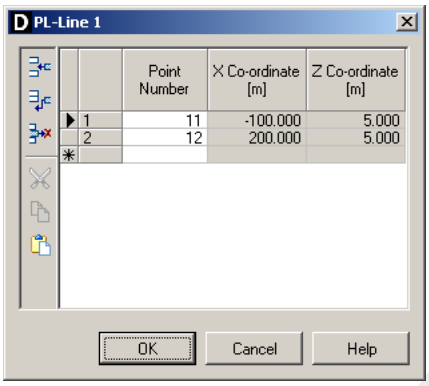


Figure 19.4: *PL-Line 1 window*

Now the PL-line levels are defined at the correct levels, they have to be assigned to the correct layers.

15. Open the *PL-lines per Layer* window from the *Geometry* menu.
16. Enter the PL–line numbers as given in Figure 19.5.

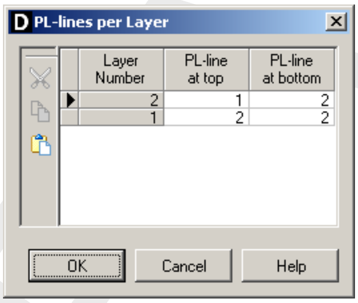


Figure 19.5: *PL-lines per Layer window*

19.4 Calculation Verticals

In the subsequent table the verticals for the location of the calculations are given.

17. Open the *Calculation Verticals* window.
18. Enter <-80> and <180> for the *First* and *Last L* values and an *Interval* of <20>.
19. Click the *Generate* button.

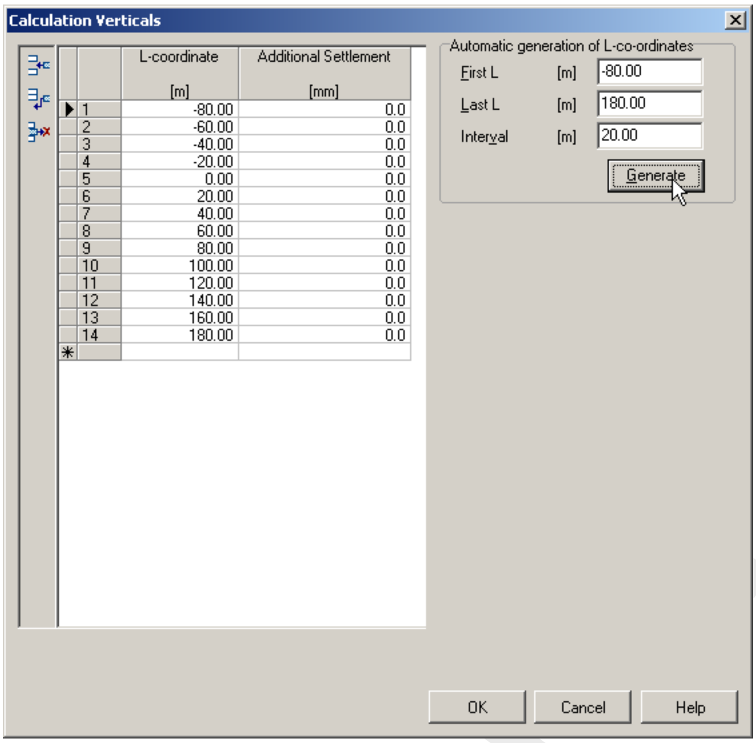


Figure 19.6: *Calculation Verticals window*

20. Click *OK* and select the *Input* tab of the *View Input* window to view the new inputs (Figure 19.7).

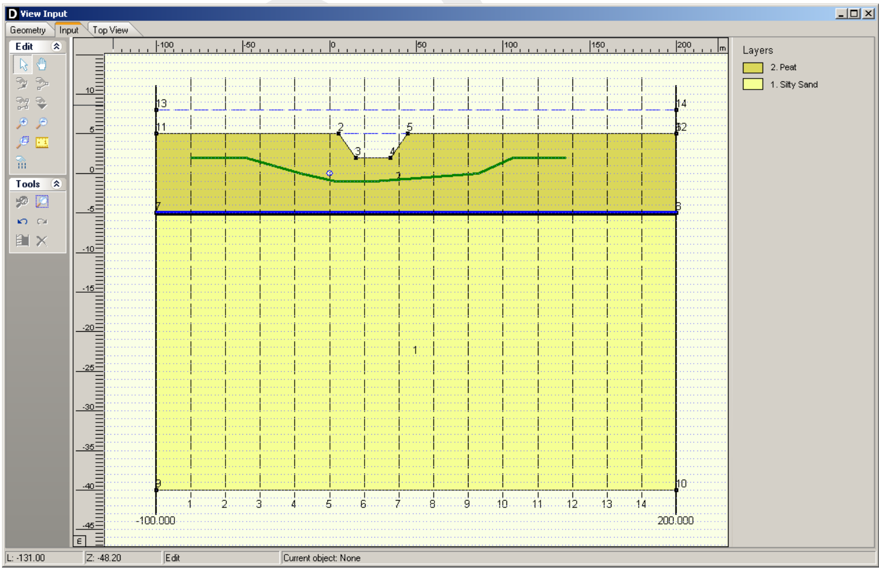


Figure 19.7: *View Input window, Input tab (Tutorial-12a)*

19.5 Factors

The required safety factors must be specified to evaluate the risk on bursting or heave of the bottom of the trench.

21. Open the *Factors* window from the *Defaults* menu.
22. Enter <1.1> and <1.2> for the *Safety factor uplift* respectively *Safety factor heave* values.
23. Click *OK*.

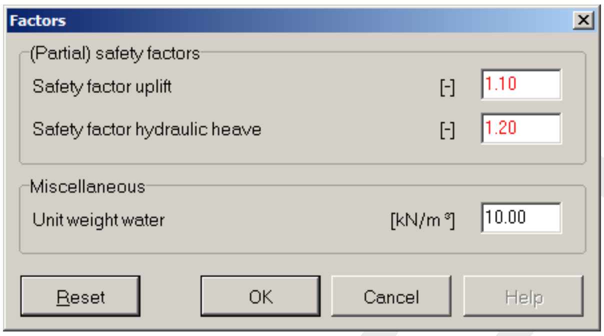


Figure 19.8: *Factors window*

19.6 Results

Now the calculations can be performed.

24. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.

19.6.1 Uplift safety for trenching in Peat layer (Tutorial-12a)

To examine the risk of uplift the graph with the uplift safety factor can be opened

25. Open the *Operation Parameters Plots* window from the *Results* menu.

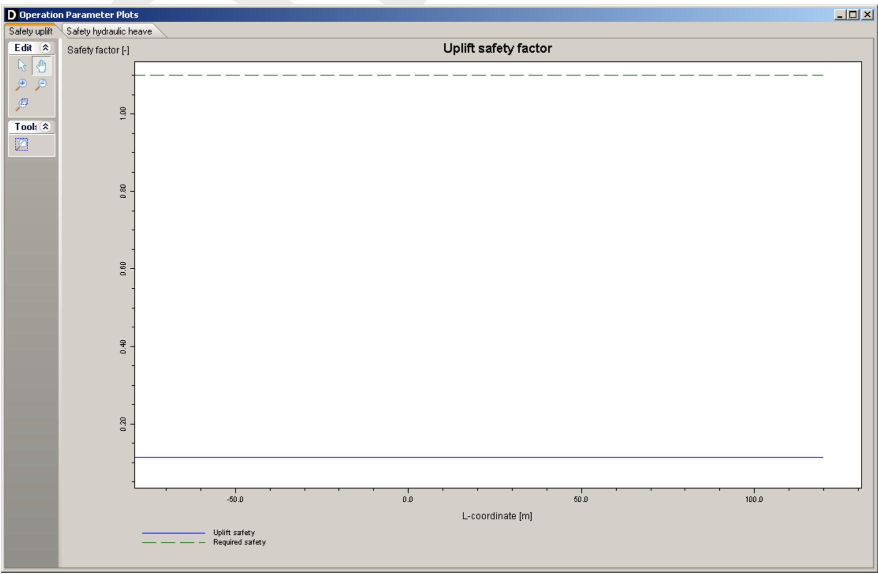
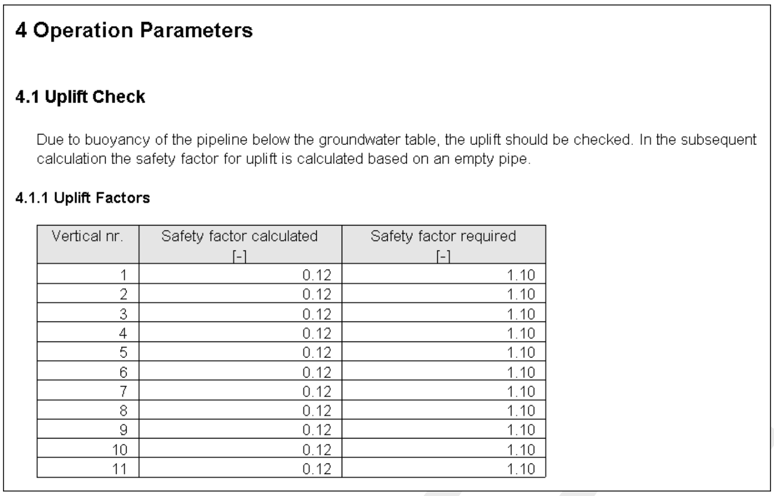


Figure 19.9: *Operation Parameter Plots window, Safety uplift tab (Tutorial-12a)*

For a detailed examination, refer to paragraph 4.1.1 of the *Report* window (Figure 19.10). As can be seen, the uplift safety of the trenched pipe is not OK as the calculated uplift factor (0.12) is lower than the required uplift factor (1.1).



4 Operation Parameters

4.1 Uplift Check

Due to buoyancy of the pipeline below the groundwater table, the uplift should be checked. In the subsequent calculation the safety factor for uplift is calculated based on an empty pipe.

4.1.1 Uplift Factors

Vertical nr.	Safety factor calculated [-]	Safety factor required [-]
1	0.12	1.10
2	0.12	1.10
3	0.12	1.10
4	0.12	1.10
5	0.12	1.10
6	0.12	1.10
7	0.12	1.10
8	0.12	1.10
9	0.12	1.10
10	0.12	1.10
11	0.12	1.10

Figure 19.10: *Report window, Uplift Factors section (Tutorial-12a)*

19.6.2 Uplift safety for trenching in Soft Organic Clay layer (Tutorial-12b)

The trench fill should be modified. The low density of the peat causes uplift problems. The effect of filling the trench with organic clay can easily be checked by changing the soil sequence.

26. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-12b>.
27. Click the *Save* button to save the current project as Tutorial 12b.
28. Click *Geometry* and select *Layers* on the menu bar to open the *Layers* window. Select the *Materials* tab (Figure 19.11) to assign the soil properties to the soil layers in the longitudinal cross section.

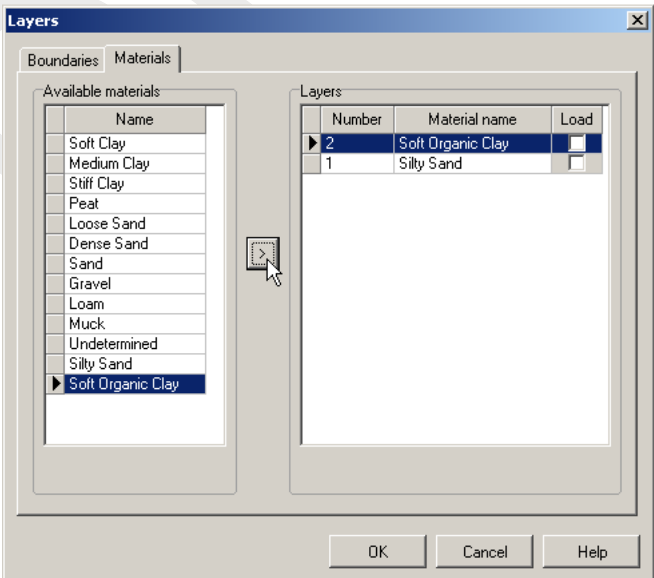
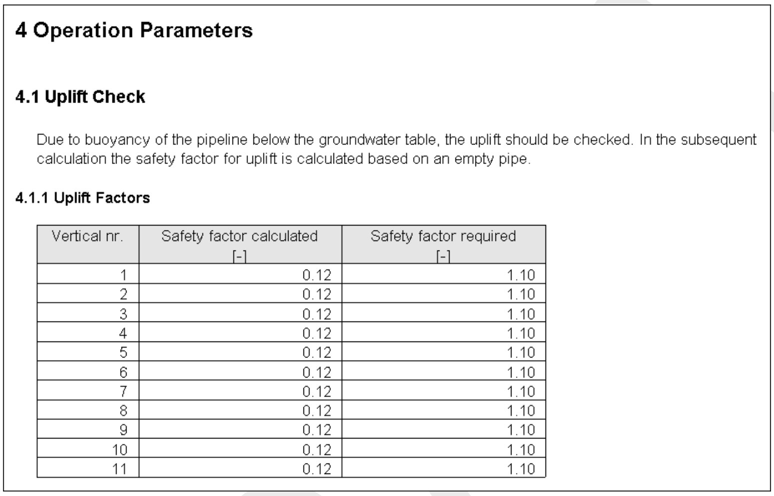


Figure 19.11: *Layers window, Materials tab (Tutorial-12b)*

29. Assign the properties of the defined layer *Soft Organic Clay* to layer *Number 2* in the longitudinal cross section. The defined properties of *Soft Organic Clay* are assigned to layer *Number 2* by clicking the *Assign* icon in between the left and the right column.
30. Click on the *OK* button to quit the window and return to the *Geometry* tab of the *View Input* window to look at the change of layers name in the legend.
31. To start the calculations again click *Calculation* and select *Start* on the menu bar or press the function key F9.
32. Open the *Operation Parameters Plots* window from the *Results* menu.
33. Open the *Report* window from the *Results* menu.
34. Go to paragraph 4.1.1 of the report (Figure 19.12). As can be seen, the uplift safety of the trenched pipe is still not OK as the calculated uplift factor (0.12) is lower than the required uplift factor (1.1).



4 Operation Parameters

4.1 Uplift Check

Due to buoyancy of the pipeline below the groundwater table, the uplift should be checked. In the subsequent calculation the safety factor for uplift is calculated based on an empty pipe.

4.1.1 Uplift Factors

Vertical nr.	Safety factor calculated [-]	Safety factor required [-]
1	0.12	1.10
2	0.12	1.10
3	0.12	1.10
4	0.12	1.10
5	0.12	1.10
6	0.12	1.10
7	0.12	1.10
8	0.12	1.10
9	0.12	1.10
10	0.12	1.10
11	0.12	1.10

Figure 19.12: *Report window, Uplift Factors section (Tutorial-12b)*

19.6.3 Hydraulic Heave Safety

To examine the risk of heave of the trench bottom the graph with the heave safety factor can be opened.

35. Select the *Safety hydraulic heave* tab of the *Operation Parameters Plots* window (Figure 19.13).

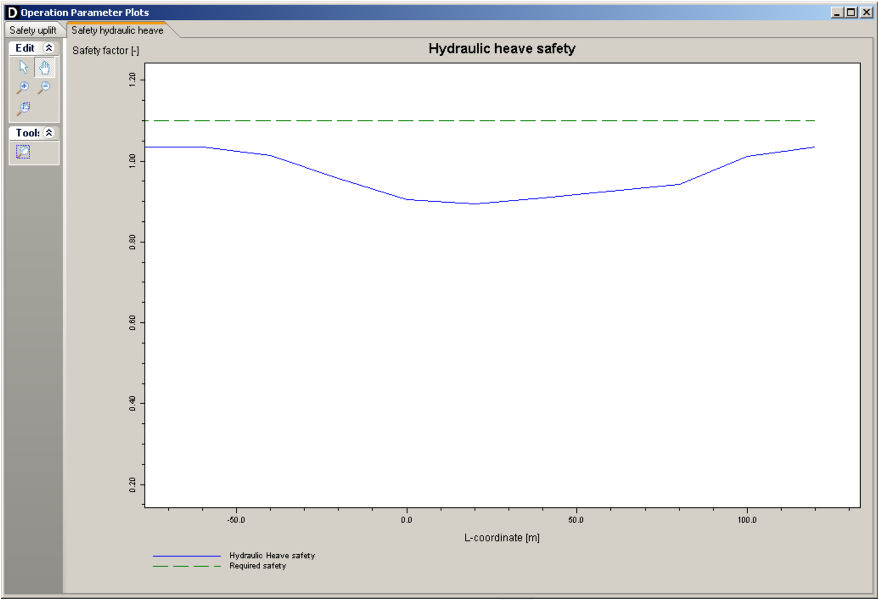


Figure 19.13: *Operation Parameter Plots window, Safety hydraulic heave tab (Tutorial-12b)*

4.2 Hydraulic Heave Check

In case of high groundwater pressures in a water bearing soillayer below the trench the safety factor for heave of the trench bottom should be evaluated. Subsequently, the safety factors for heave are based on groundwater pressures at the top of layer:1 (Silty Sand) are calculated

4.2.1 Hydraulic heave of the trench bottom

Vertical nr.	Safety factor calculated [-]	Safety factor required [-]
1	1.03	1.20
2	1.03	1.20
3	1.01	1.20
4	0.96	1.20
5	0.90	1.20
6	0.89	1.20
7	0.91	1.20
8	0.93	1.20
9	0.94	1.20
10	1.01	1.20
11	1.03	1.20

Figure 19.14: *Report window, Hydraulic heave of the trench bottom section (Tutorial-12b)*

Note: In the report (Figure 19.14) the hydraulic heave safety of the trenched pipe is not OK for all verticals, the calculated safety factors are lower than the required safety factor specified at the default factors. Especially below the waterway the risk on bursting or heave of the bottom of the trench is relatively high.

19.7 Lowering the hydraulic head (Tutorial-12c)

The problem of heave of the bottom of the trench can be solved by drainage of the subsequent silty sand layer. By dewatering the silty sand layer, the hydraulic head can be lowered to the required level. Lowering the level of the hydraulic head in the silty sand layers can be done as follows:

36. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename

the file into <Tutorial-12c>.

37. Click the *Save* button to save the current project as Tutorial 12c.
38. Return to the *Geometry* tab of the *View Input* window and select the button *Add point(s) to boundary / PL-line* .
39. Click the four additional points on PL-line 2 as shown in Figure 19.15 (points 15 to 18).
40. Click the *Geometry* option from the menu bar and select the option *Points*. In the *Points* window, enter the co-ordinates of points 15 to 18 (i.e. PL-line number 2 for the hydraulic head in the sand layer) as given in Figure 19.16.

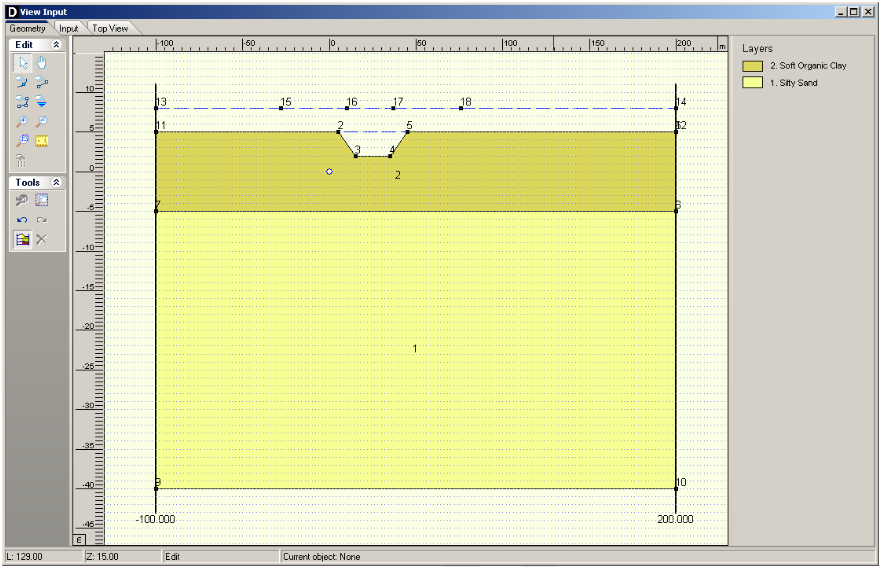
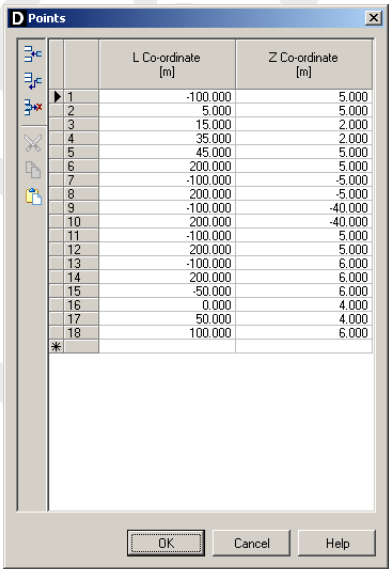


Figure 19.15: *View Input window, Geometry tab (Tutorial 12c)*



Points

	L Co-ordinate [m]	Z Co-ordinate [m]
1	-100.000	5.000
2	5.000	5.000
3	15.000	2.000
4	35.000	2.000
5	45.000	5.000
6	200.000	5.000
7	-100.000	-5.000
8	200.000	-5.000
9	-100.000	-40.000
10	200.000	-40.000
11	-100.000	5.000
12	200.000	5.000
13	-100.000	6.000
14	200.000	6.000
15	-50.000	6.000
16	0.000	4.000
17	50.000	4.000
18	100.000	6.000

OK Cancel Help

Figure 19.16: *Points window (Tutorial 12c)*

Now the results can be checked:

41. Start the calculations by clicking *Start* on the *Calculation* menu bar or by pressing the function key F9.

42. Open the *Operation Parameter Plots* window from the *Results* menu and select the *Safety hydraulic heave* tab.

From the plots (Figure 19.17), it is clear that the drainage yields a higher calculated safety factor for hydraulic heave safety.

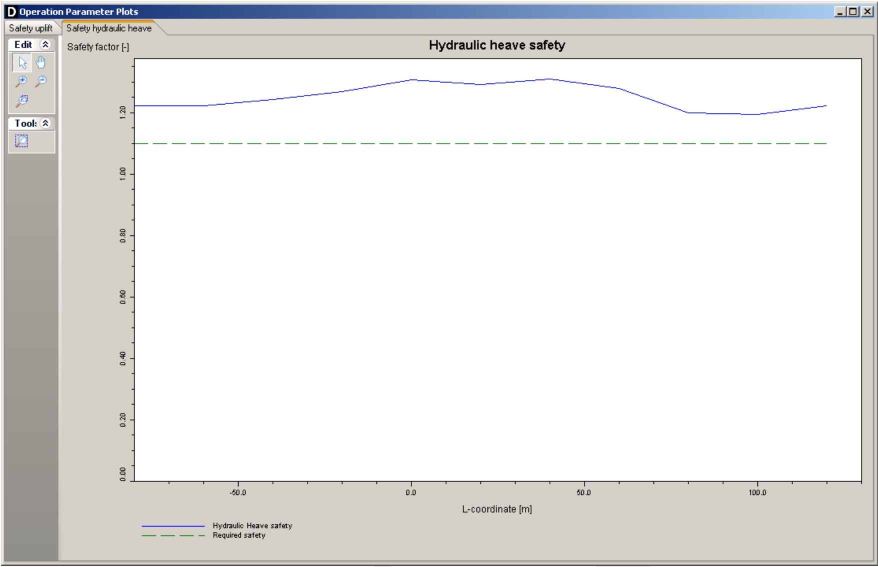


Figure 19.17: *Operation Parameter Plots windows, Safety hydraulic heave tab (Tutorial 12c)*

43. Open the *Report* window to look at the calculated values (Figure 19.18): the minimum calculated safety factor for *Hydraulic Heave* is 1.46 which is more than the required factor of 1.20.

4.2 Hydraulic Heave Check

In case of high groundwater pressures in a water bearing soillayer below the trench the safety factor for heave of the trench bottom should be evaluated. Subsequently, the safety factors for heave are based on groundwater pressures at the top of layer:1 (Silty Sand) are calculated

4.2.1 Hydraulic heave of the trench bottom

Vertical nr.	Safety factor calculated [-]	Safety factor required [-]
1	1.22	1.20
2	1.22	1.20
3	1.24	1.20
4	1.27	1.20
5	1.31	1.20
6	1.29	1.20
7	1.31	1.20
8	1.28	1.20
9	1.20	1.20
10	1.20	1.20
11	1.22	1.20

Figure 19.18: *Report windows, Hydraulic heave of the trench bottom section (Tutorial 12c)*

20 Tutorial 13: Face support and Thrust force for the Direct Pipe method

This tutorial considers installation of a pipeline using the direct pipe method. The pipeline consists of steel pipe sections. The exercise focuses on the basic calculation set up for direct pipe in D-GEO PIPELINE.

The objectives of the exercise are:

◇ To make a schematization of the pipeline installation by direct pipe;
◇ To evaluate the minimal required and maximal allowable shield pressure at the face of the tunneling machine;
◇ To evaluate the thrust force.

The following modules are needed:

◇ D-GEO PIPELINE Standard module (HDD)
◇ Direct Pipe module

The result of this tutorial is presented in the file Tutorial-13.dri.

20.1 Introduction to the case

The direct pipe method enables to lay a prefabricated pipeline in one single, continuous working operation into the ground with the aid of the thrust unit “pipe thrust”. As with pipe jacking, earth excavation is executed by means of a navigable micro tunnelling machine, which is directly coupled with the pipeline. The tunnel face is slurry supported; a bentonite suspension is often used for controlled excavation of the soil.

In this tutorial a steel pipeline in a single sand layer is modeled. The calculated shield pressure will be evaluated as well as the thrust force. The pipeline configuration is shown in Figure 20.1.

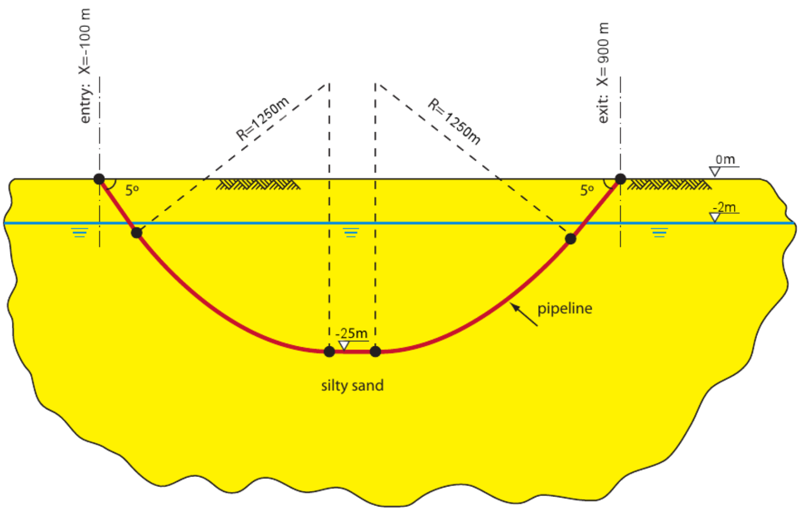


Figure 20.1: *Pipeline configuration for Tutorial 13*

The soil properties of the silty sand layer are provided in Table 20.1.

Table 20.1: *Properties of the silty sand layer (Tutorial 13)*

Dry unit weight	[kN/m^3]	18
Wet unit weight	[kN/m^3]	20
Cohesion	[kN/m^2]	0
Angle of internal friction	[°]	30
Undrained strength top	[kN/m^2]	0
Undrained strength bottom	[kN/m^2]	0
E modulus top	[kN/m^2]	10000
E modulus bottom	[kN/m^2]	15000
Adhesion	[kN/m^2]	0
Friction angle (Delta)	[°]	20
Poisson's ratio	[-]	0.35

The pipeline material used in this tutorial is a steel 480 with the properties given in Table 20.2.

Table 20.2: *Properties of steel material (Tutorial 13)*

Pipe material		Steel 480
Outer diameter	[mm]	1219
Overcut	[mm]	38
Wall thickness	[mm]	22.7
Young's modulus	[N/mm^2]	205800
Unit weight pipe material	[kN/m^3]	7.85

This tutorial starts with the selection of the pipeline installation model.

20.2 Model selection

The direct pipe model must be selected to carry out the current tutorial.

noitemsep

1. Click *File* and choose *New* on the menu bar to start a new project.
2. In the *New File* window select the option *New geometry* to start. This will result in an empty geometry.
3. Save the project by clicking *Save As* in the *File* menu and by entering <Tutorial-13> as project name.
4. Click *Save* to close this window.
5. On the menu bar, click *Project* and then choose *Model* to open the *Model* window (Figure 20.2).
6. Select *Direct pipe* and click *OK*.

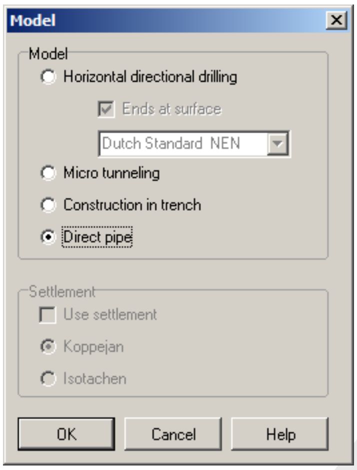


Figure 20.2: *Model window*

7. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
8. Fill in $<$Tutorial 13 for D-GEO PIPELINE $>$ and $<$Pipeline installation by direct pipe$>$ for *Title 1* and *Title 2* respectively in the *Identification* tab.
9. In the other tab of the *Project Properties* window, modify (if not already done) some defaults values according to Figure 20.3 in order to make the graphical geometry more understandable.
10. Click *OK*.

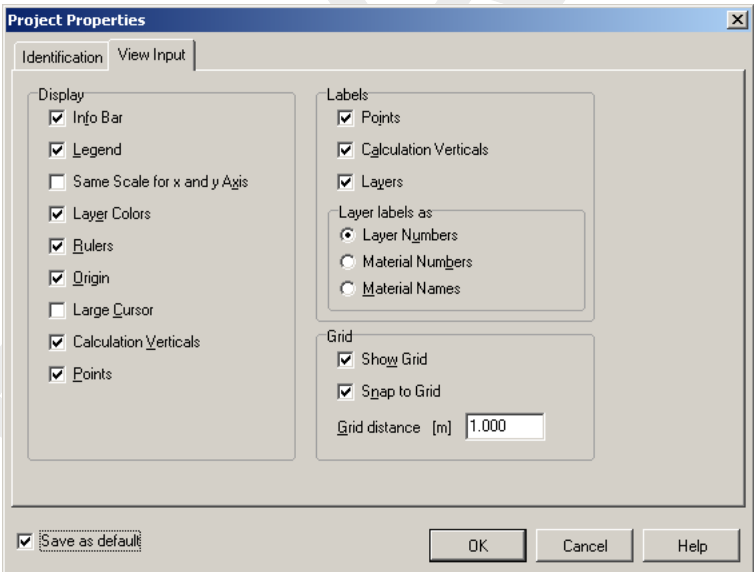


Figure 20.3: *Project Properties window, View input tab*

20.3 Geometry

Firstly, the geometry of Figure 20.1 needs to be given in D-GEO PIPELINE. In order to do this, the following actions should be performed:

11. First enlarge the dimensions of the geometry window by selecting the left boundary by clicking the left mouse button, then click the right button and select *Properties.* This will result in the coordinate window for the left boundary as shown in Figure 20.4. Enter coordinate X of < -100 m$>$.

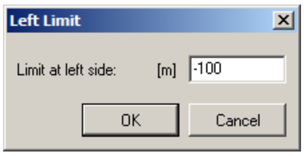


Figure 20.4: *Left Limit window*

12. Repeat the previous described actions for the right boundary and shift the boundary to coordinate X of $<$900 m$>$. The width in between the left and the right boundary is now 1000 m.
13. Select the drawing button *Zoom limits* from the *Tools* panel so that the drawn geometry appears in the center of the screen.
14. Unselect the drawing button *Automatic regeneration of geometry on/off* from the *Tools* panel.
15. Select the drawing button from the *Edit* panel *Add single line* to draw the surface line of the longitudinal cross section of the horizontal directional drilling and position the straight surface line at Z = 0 m. Use the right mouse button to finish the line.
16. Select again the drawing button *Add single line* to draw the lower boundary of the longitudinal cross section of the horizontal directional drilling and position the straight lower boundary line at Z = –30 m. Use the right mouse button to finish the line.
17. Select the drawing button *Automatic regeneration of geometry on/off* from the *Tools* panel so that the geometry as shown in Figure 20.5 appears.
18. Select the drawing button *Add pl-line(s)* from the *Edit* panel and position the level of the groundwater at coordinate Z = –2 m. Use the right mouse button to finish the line. The blue dashed line represents the groundwater line (PL line).

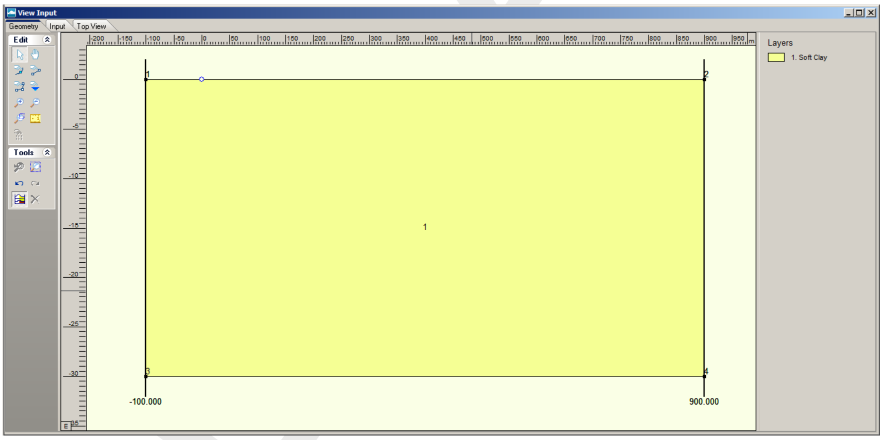


Figure 20.5: *View Input window, Geometry tab*

20.3.1 Soil layer properties

The properties of the soil layers should be specified in the menu materials, which can be entered by clicking soil. In this tutorial only one soil layer is considered.

19. Click *Soil* and select *Materials* on the menu bar to open the *Materials* window (Figure 20.6) and enter the soil data.
20. Add a new material by choosing *Add* button below the materials list on the left side of the window with the new <Silty Sand>.
21. Enter the soil data as given in Table 20.1.
22. Finish the input of soil data by clicking *OK*.

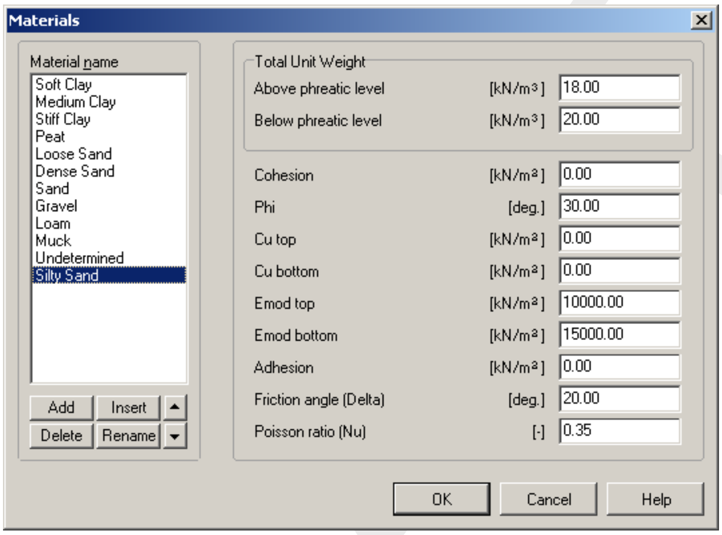


Figure 20.6: *Materials window*

The defined soil properties and the groundwater level have to be assigned to the drawn geometry of the longitudinal cross section. The assignments can be carried out by clicking geometry and choosing the subsequent described options on the menu bar.

20.3.2 Phreatic Line

23. On the *Geometry* menu, select *Phreatic Line* to open *Phreatic Line* window (Figure 20.7) in which the phreatic line for calculation of the groundwater pressures can be selected.
24. Choose PL–line nr. <1> (only one phreatic line is available) and click *OK*.

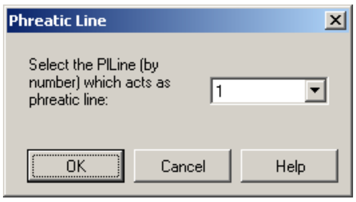


Figure 20.7: *Phreatic Line window*

20.3.3 Layers

25. Click *Geometry* and select *Layers* on the menu bar to assign the soil properties to the soil layers in the longitudinal cross section. To assign a material to a layer, select the *Material* tab.

26. Assign the properties of the defined layer *Silty Sand* to layer nr 1 in the longitudinal cross section. The available soil layers with defined properties are shown in left column of the materials window. The layers in the longitudinal cross section are shown in the right column of the materials window. The defined properties are assigned to layer nr 1 by clicking the arrow in between the columns. This will result in the *Material* tab shown in Figure 20.8.

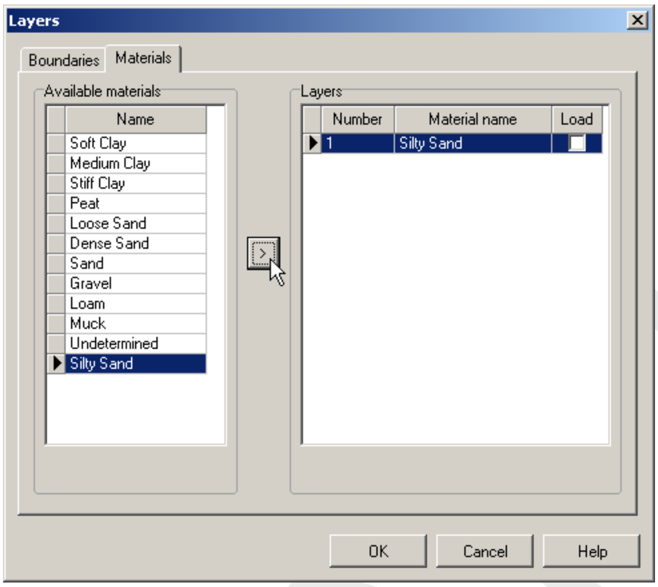


Figure 20.8: *Layers window, Materials tab*

27. Click *OK* to quit the window and return to the geometry window to watch the change of layer name in the legend.

20.3.4 PL-Lines per Layers

28. Click *Geometry* and select *PL–lines per Layers* on the menu bar to open the *PL–lines per Layer* window (Figure 20.9) in which the defined PL–lines to the soil layers in the longitudinal cross section can be defined. This window contains the information for the calculation of the groundwater pressure distribution. In this tutorial only one PL-line is defined. The groundwater pressure at the top of the silty sand layer and the bottom of this layer should be calculated based on the hydraulic head of PL-line 1.
29. Click *OK* to close the window.

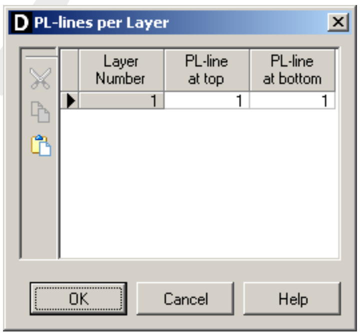


Figure 20.9: *PL-lines per Layers window*

20.3.5 Check Geometry

30. The geometry can be tested by clicking *Geometry* and selecting *Check Geometry* on the menu bar. If the geometry is entered properly, the message shown in Figure 20.10 appears.
31. Click *OK* to close the window.

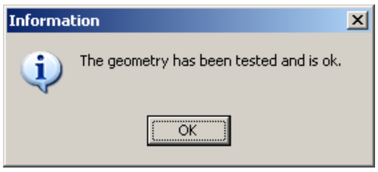


Figure 20.10: *Check Geometry window*

20.4 Pipeline Configuration

Installation of a pipeline using the direct pipe method starts with the pipeline on rollers before it enters the soil. The pipe will enter and exit the soil with an angle of 5 degrees, has a bending radius of 1250 meters and the lowest level of the pipe is at a level of 25 m below surface. In this tutorial we use a pipeline with segments, if there is a case without segments, the value of the segment length is a value longer than the total pipelength.

32. Click *Pipe* from the menu and select *Pipeline Configuration* to open the *Pipeline Configuration* window.
33. Enter the values as presented in Figure 20.11.

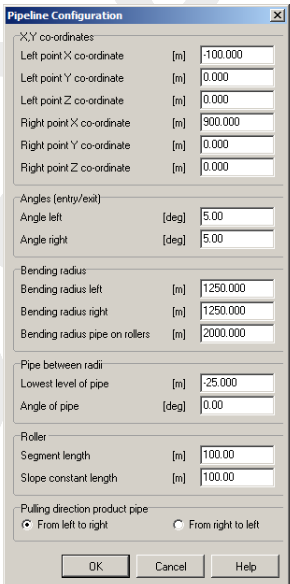


Figure 20.11: *Pipeline Configuration window*

34. Click *OK* to confirm.
35. Now examine the direct pipe trajectory in the *Input* tab (Figure 20.12) and *Top View* tab of the *View Input* window.

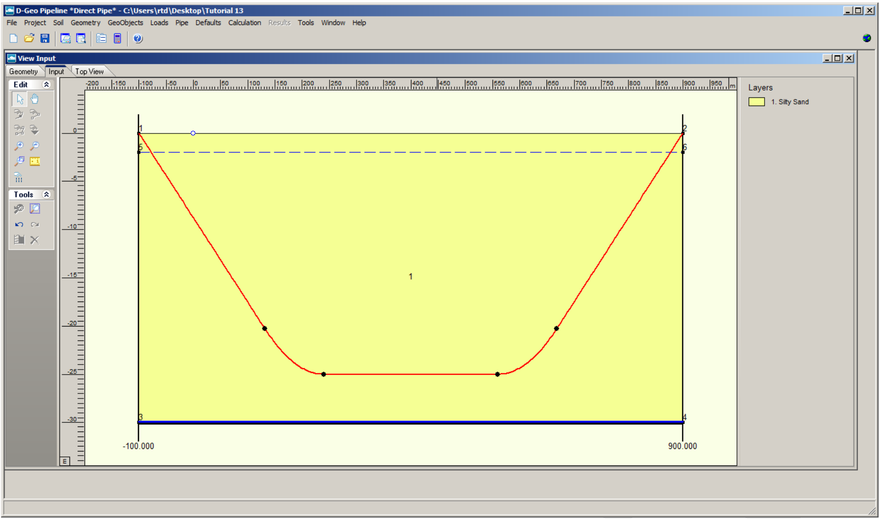


Figure 20.12: View Input window, Input tab

20.5 Pipe Material Data

The pipe material of the pipe which will be installed by the direct pipe method is chosen. The characteristics of the pipe must be specified as well.

36. Click *Pipe* from the menu and select *Product Pipe Material Data* to open the *Product Pipe Material Data* window.
37. Enter the values as presented in Figure 20.13.

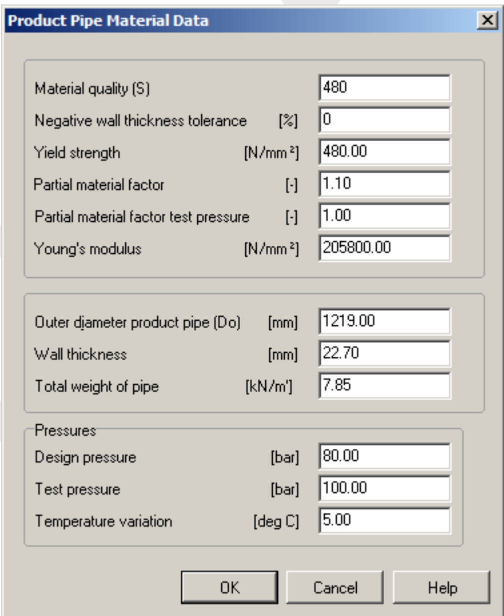


Figure 20.13: Product Pipe Material Data window

20.6 Soil behavior

The strength of soil layers is dependent on the drained or undrained behavior of soil layers during application the drilling fluid pressure at the front of the MTBM. Depending on the permeability of the soil layer, the soil will behave drained or undrained. A Sand layer is a well permeable so called drained frictional material. The strength of this soil layer can be cal-

culated using the drained (effective) strength parameters effective cohesion (c) and angle of internal friction (φ). In case of undrained behavior in other soil types, the strength of the soil can be calculated using the undrained strength parameter undrained cohesion (c_u).

38. Click *GeoObjects* and select *Boundaries Selection* on the menu bar to open the *Boundaries Selection* window for specification of the soil behavior.
39. Choose the boundary between the undrained and drained layer on top of layer nr <1> (Figure 20.14). This choice results in drained behavior of layer nr 1.
40. Choose the boundary between the compressible and incompressible layer on top of layer nr <1>. This choice results is used for the calculation of the soil mechanical parameters. Compressible layers yield higher soil loads on the pipeline due to incomplete arching.
41. Click *OK* to close this window.

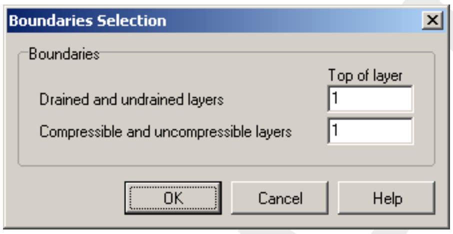


Figure 20.14: *Boundaries Selection window*

20.7 Calculation Verticals

The locations in the longitudinal cross section at which a calculation should be carried out must be specified by the user. The user is able to perform calculations at uniform distances along the longitudinal cross section but is also able to perform more calculations at short distances at locations of interest.

42. Click *GeoObjects* and select *Calculation Verticals* on the menu bar to select the *Calculation Verticals* window for specification of the calculation locations along the longitudinal cross section.
43. Choose the *Automatic generation of L co-ordinates* option on the right side of the window and choose the following values: <–50 m> for *First*, <850 m> for *Last* and <50 m> for *Interval*.
44. Click on the *Generate* button and watch the result of automatic vertical generation on the left side of the *Calculation Verticals* window. This will result in the window shown in Figure 20.15.
45. Click *OK* to confirm the selected verticals and switch to the input window to watch the location of the verticals in the longitudinal cross section.

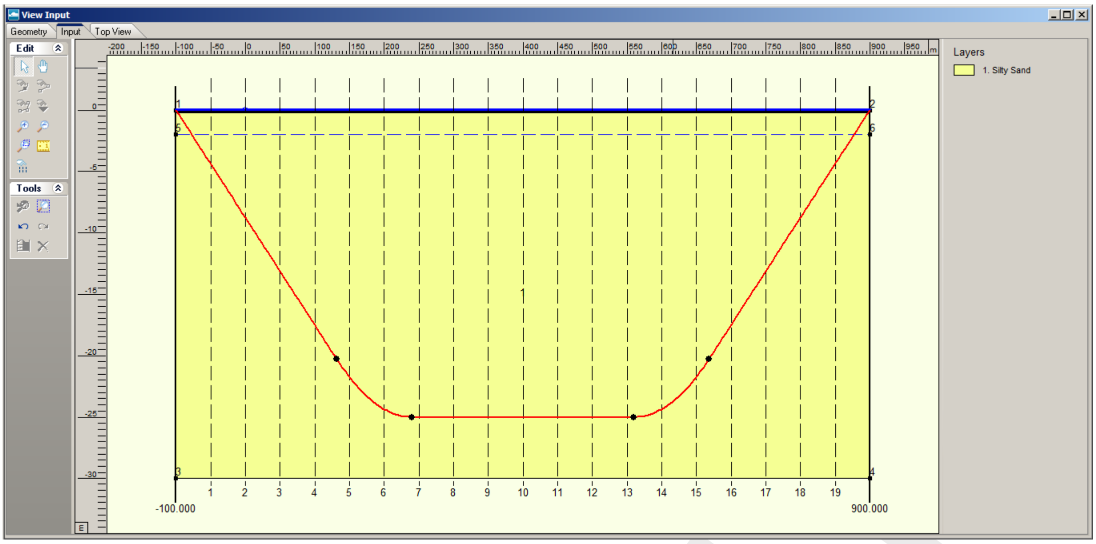


Figure 20.15: *Calculation Verticals window*

20.8 Engineering Data

46. Select *Engineering Data* from the *Pipe* menu bar to open the *Engineering Data* window.
47. Enter the values as given in Figure 20.16.

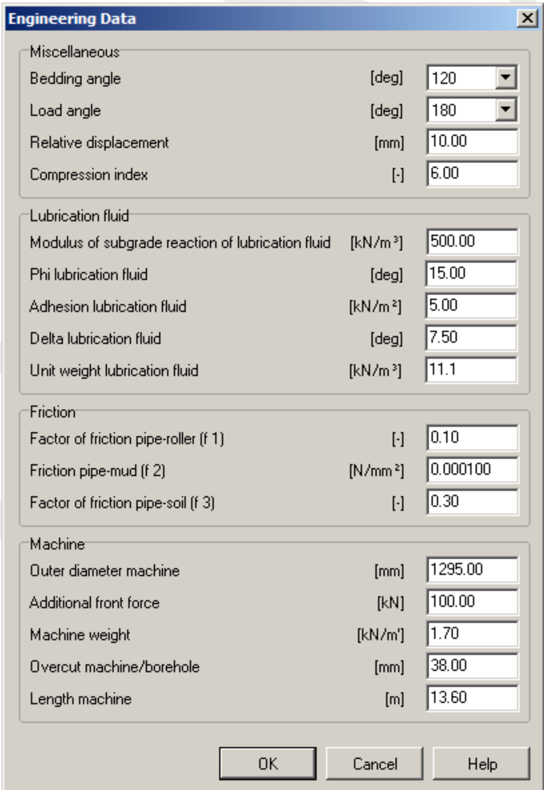


Figure 20.16: *Engineering Data window*

20.9 Results: Operation Parameter Plots

Tutorial 8 (chapter 15) explains the effects of using a micro-tunneling machine and it's face support pressure. In this tutorial as well, the soil layer which consists of silty sand exhibits drained soil behavior.

A maximum support pressure should not be exceeded to prevent uplift of the soil above the micro-tunneling machine or a blow out of drilling fluid towards the surface. The support pressure, at which the soil deformations are minimal during drilling should be in between the two limits. At the neutral pressure, the face support pressure is in equilibrium with the current horizontal soil pressure.

48. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.
49. Click *Results* and select *Operation Parameter Plots* from the menu bar to open the *Operation Parameter Plots* window.

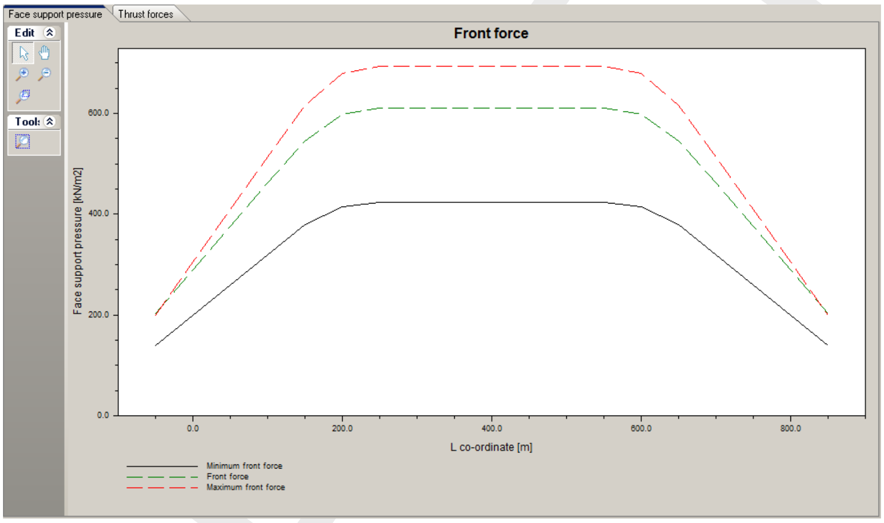


Figure 20.17: *Operation Parameter Plots window, Face support pressure tab*

From the graph (Figure 20.17) it can be observed that for this simple tutorial situation the target face support pressure during the pipeline installation is between the determined limits of the maximum allowable face support pressure and the minimum required face support pressure.

20.10 Results: Thrust Force

50. Open the *Operation Parameter Plots* window from the *Results* menu and select the *Thrust forces* tab (Figure 20.18).

This graph shows the calculated thrust force versus the length of pipe jacked into the subsurface. The thrust forces are allowable. It should be mentioned that the capacity of the jacks is limited. In general the maximum capacity is about 600 ton (6000 kN) so that for larger lengths intermediate jacks are required.

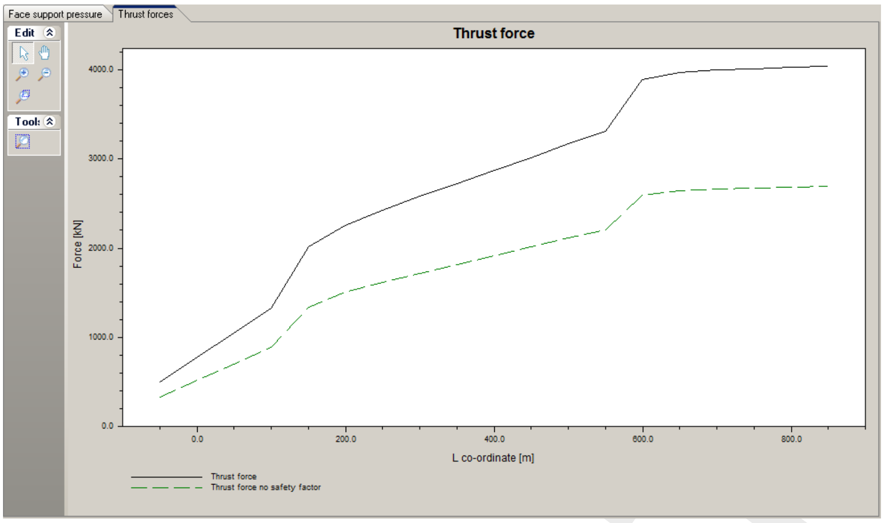


Figure 20.18: *Operation Parameter Plots window, Thrust Force tab*

21 Tutorial 14: Stress Analysis Direct Pipe

This tutorial considers installation of a pipeline using the direct pipe method. The pipeline consists of steel pipe sections. The exercise focuses on the stress analysis for direct pipe in D-GEO PIPELINE.

The objectives of the exercise are:

◇ To evaluate the stress analysis.

The following modules are needed:

◇ D-GEO PIPELINE Standard module (HDD)
◇ Direct Pipe module

The result of this tutorial is presented in the file Tutorial-14.dri.

21.1 Introduction to the case

In D-GEO PIPELINE it is assumed that the pipeline remains fixed at the specified location and that settlement of the soil layers below the pipeline does not influence the pipeline. Therefore a relative simple pipe stress analysis can be performed.

The stresses in the pipeline are calculated for the different installation stages. According NEN 3650 an additional calculation is made for application of internal pressure on the pipeline. Therefore in the stress analysis according the NEN 3650, four Load Combinations (LC) are considered:

◇ LC 1A: start of the thrust operation
◇ LC 1B: maximum thrust force
◇ LC 2: application of internal pressure on the pipeline
◇ LC 3: pipeline in operation, without internal pressure
◇ LC 4: pipeline in operation, with internal pressure

The calculated stresses are assessed according NEN 3650 and NEN 3651.

In this tutorial the pipeline configuration is the same as in the previous tutorial, but the soil sequence is different. The properties of the two layers are given in Table 21.1. The pipeline configuration is shown in Figure 21.1.

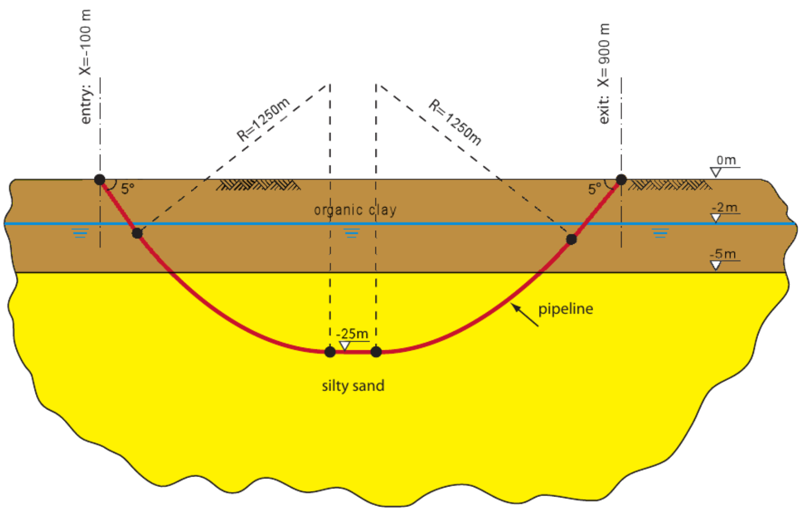


Figure 21.1: *Pipeline configuration for Tutorial 14*

Table 21.1: *Layer properties (Tutorial 14)*

		Silty sand	**Soft organic clay**
Dry unit weight	[kN/m^3]	18	13
Wet unit weight	[kN/m^3]	20	13
Cohesion	[kN/m^2]	0	2
Angle of internal friction	[°]	30	18
Undrained strength top	[kN/m^2]	0	10
Undrained strength bottom	[kN/m^2]	0	30
E modulus top	[kN/m^2]	10000	500
E modulus bottom	[kN/m^2]	15000	1000
Adhesion	[kN/m^2]	0	2
Friction angle	[°]	20	12
Poisson's ratio	[-]	0.35	0.45

This tutorial is based on continuation of the file used in Tutorial 13 (chapter 20).

1. Click *File* and select *Open* on the menu bar to open the *Open* window.
2. Select *Tutorial-13* and click the *Open* button to open the file.
3. Click *File* and select *Save as* on the menu bar to open the *Save As* window and rename the file into <Tutorial-14>.
4. Click the *Save* button to save the file for Tutorial 14.
5. On the menu bar, click *Project* and then choose *Properties* to open the *Project Properties* window.
6. Fill in <Tutorial 14 for D-GEO PIPELINE > and <Direct Pipe: stress analysis> for *Title 1* and *Title 2* respectively in the *Identification* tab.
7. Click *OK*.

21.2 Geometry

This tutorial considers a layered soil sequence. An organic clay layer on top of a silty sand layer will be considered. The new soil layers should be specified in the geometry window.

8. In the *View Input* window, switch to the *Geometry* tab to edit the existing soil layer sequence.
9. Click the *Add single line(s)* button from the *Edit* panel to draw an additional line which represents the lower boundary of the peat layer on top of the silty sand layer. Place the boundary at Z = -5 m. Click the right mouse button to escape from the single line drawing.
10. Click the *Zoom limits* button from the *Tools* panel so that the drawn geometry appears in the center of the screen.

21.3 Soil layer properties

The properties of the soil layers in the layered soil sequence should now be specified.

11. Click *Soil* and select *Materials* on the menu bar to open the *Materials* window (Figure 20.6) and enter the soil data.
12. Add a new material by choosing *Add* button below the materials list on the left side of the window with the new <Organic Clay>.
13. Enter the soil data as given in Table 21.1.
14. Finish the input of soil data by clicking *OK*.

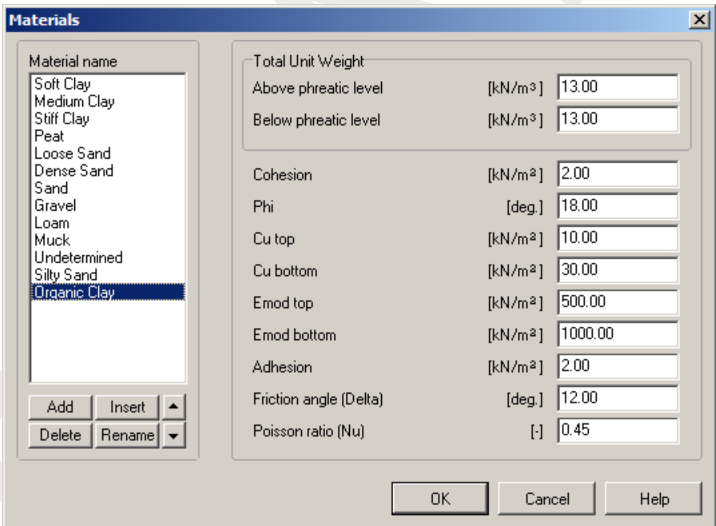


Figure 21.2: *Materials window*

The defined soil properties have to be assigned to the drawn geometry of the longitudinal cross section. The assignments can be carried out in the *Geometry* menu.

15. Click *Geometry* and select *Layers* on the menu bar to open the *Layers* window.

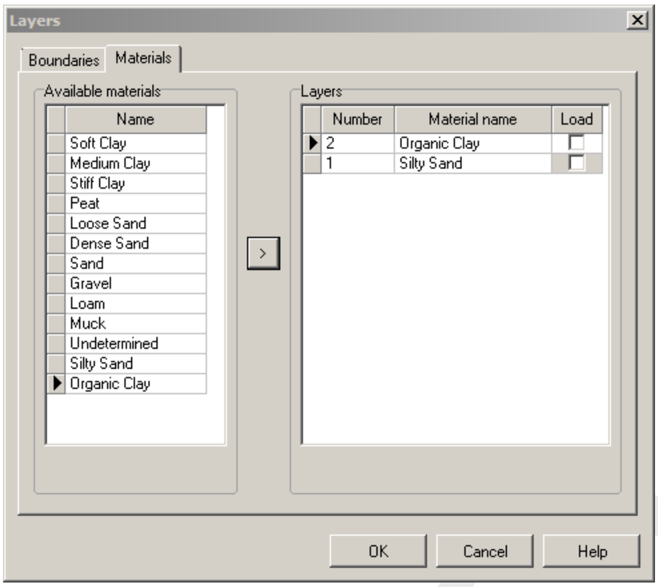


Figure 21.3: *Layers window, Materials tab*

16. Select the *Materials* tab.
17. Assign the properties of the defined layer *Organic Clay* to layer number 2 in the longitudinal cross section by clicking the *Assign* icon in between the left and the right column.
18. Click on the *OK* button to quit the window and return to the *Geometry* tab of the *View Input* window to look at the change of layers name in the legend (Figure 21.4).

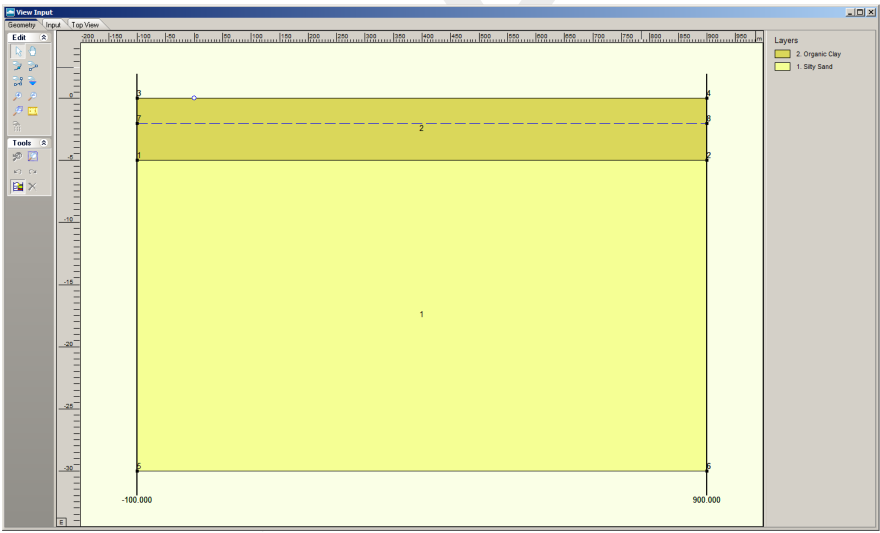


Figure 21.4: *View Input window, Geometry tab*

19. The geometry can be tested by clicking *Geometry* on the menu bar and selecting *Check Geometry*. If the geometry is entered properly, the message *Geometry has been tested and is OK* appears.
20. Click *OK* to close this window.

21.4 Soil behavior

Strength of soil layers is dependent on the drained or undrained behavior of soil layers during application the drilling fluid pressure. Depending on the permeability of the soil layer, the soil will behave drained or undrained. The *Silty Sand* layer is well permeable so that the behavior

of the silty sand layer is drained. The strength of this soil layer can be calculated using the drained (effective) strength parameters effective cohesion (c) and angle of internal friction (φ). In case of undrained behavior in the impermeable *Organic Clay* layer, the strength of the soil can be calculated using the undrained strength parameter undrained cohesion (c_{u}).

The soil load on the pipeline after finishing the installation is dependent on the soil pipeline interaction, which is in turn largely dependent on the soil behavior. As described in section 10.2, arching develops completely in incompressible soil layers, while in compressible layers the reduced soil load on the pipeline is higher due to compression of the soil next to the pipeline.

21. Click *GeoObjects* and select *Boundaries Selection* on the menu bar to open the *Boundaries Selection* window for specification of the soil behavior.
22. Choose the boundary between the *Drained and undrained layers* on top of layer number $<1>$ (Figure 21.5). This choice results in drained behavior of layer number 1.
23. Choose the boundary between the *Compressible and uncompressible layers* on top of layer number $<1>$. This choice results in full development of arching in layer number 1 while in layer number 2 arching is not fully developed.
24. Click *OK* to close this window.

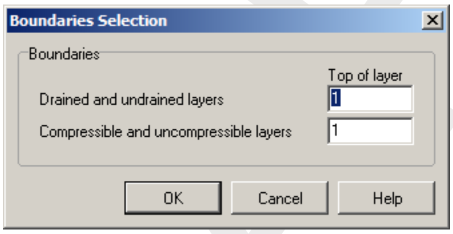


Figure 21.5: *Boundaries Selection window*

21.5 Calculation and Results

The results of the calculation are shown in the D-GEO PIPELINE report which is created automatically after finishing the calculations.

25. To start the calculations click *Calculation* and select *Start* on the menu bar or press the function key F9.

The pipe stress analysis is described in the report. For each load combination the axial and tangential stresses in the product pipe are calculated. The stresses are used to calculate the maximum combined stress in the pipeline.

26. Click *Results* and select *Report* on the menu bar to watch the results of the calculated axial and tangential stresses for each load combination/installation stage in paragraph 5.2 (see Figure 21.6).

5.2 Results Stress Analysis

In the calculation 5 load combinations are considered:

- Load combination 1A: start Thrust operation
- Load combination 1B: Maximum thrust force
- Load combination 2: application internal pressure
- Load combination 3: pipeline in operation, no inner pressure
- Load combination 4: pipeline in operation, pressure applied

The nominal wall thickness is 22.7 mm. The calculation hereafter will prove that the pipeline wall thickness is sufficient. The calculations are in accordance with NEN 3650 and NEN 3651.

Figure 21.6: *Report window, Results Stress Analysis*

27. Continue looking at the report and scroll down to paragraph 5.3. In the table in paragraph 5.3, the stress assessment is carried out: the calculated stresses are compared with the yield strength of steel according to the specifications described in NEN 3650. Below the stress assessment table, the results of the deflection calculation are given (see Figure 21.7).

5.3 Check on Calculated Stresses

According to NEN 3650-2 art.5 D.3.1 the calculated stresses for the load combinations, must meet the following conditions (note: Re = 480 [N/mm²]) :

Load combination 1
Sigma_v =< Re/Gamma_m

Load combination 2
- Sigma_ptest =< Re/Gamma_test
- Sigma_py =< Re/Gamma_m
- Sigma_pm =< 1.1·Re/Gamma_m

Load combinations 3 and 4
- Sigma_vmax =< 0.85(Re+Re_20deg)/Gamma_m

All stresses in all conditions are allowable.

	Max allowable stress [N/mm²]	Load combination1A	Load combination1B	Load combination2	Load combination3	Load combination4
Sigma_v	436.36	81	201	-	-	-
Sigma_ptest	480.00	-	-	290	-	-
Sigma_py	436.36	-	-	264	-	-
Sigma_pm	480.00	-	-	228	-	-
Sigma_vmax	741.82	-	-	-	536	417

Figure 21.7: *Report window, Check on calculated stresses*

28. Notice that the calculated stresses for all load combinations are allowable. The deflection is lower than the allowable value.
29. Look at the calculated soil load and the calculated modulus of subgrade reaction on paragraph 4.1.

4 Soil Mechanical Parameters

4.1 Soil Mechanical Parameters

The list with data and issues is shown hereafter:
Note: safety factors not applied

Pv;p	Passive soil load	kN/m²
Pv;n	Neutral soil load	kN/m²
Ph;n	Neutral horizontal soil load	kN/m²
Pv,r;n	Reduced neutral soil load	kN/m²
kv;top	Vertical modulus of subgrade reaction (bilinear) upward	kN/m³
kv;top,max	Vertical modulus of subgrade reaction upward	kN/m³
dv	Vertical displacement	mm
kv	Vertical modulus of subgrade reaction downward	kN/m³
Pv;e	Vertical bearing capacity	kN/m²
kh	Horizontal modulus of subgrade reaction	kN/m³
Ph;e	Horizontal bearing capacity	kN/m²
tmax	Maximal friction pipe-lubricant	kN/m²
dmax	Displacement at maximal friction	mm

Vertical nr.	Pv;p [kN/m²]	Pv;n [kN/m²]	Ph;n [kN/m²]	Pv,r;n [kN/m²]	kv,top [kN/m³]
1	61	32	22	32	241
2	201	68	34	68	2108
3	450	111	56	111	3965
4	744	155	78	155	4301
5	901	198	99	198	4628
6	994	224	112	224	4830
7	1017	230	115	230	4881
8	1017	230	115	230	4881
9	1017	230	115	230	4881
10	1017	230	115	230	4881
11	1017	230	115	230	4881
12	1017	230	115	230	4881
13	1017	230	115	230	4881
14	994	224	112	224	4830
15	901	198	99	198	4628
16	744	155	78	155	4301
17	450	111	56	111	3965
18	201	68	34	68	2108
19	61	32	22	32	241

Vertical nr.	dv [mm]	kv [kN/m³]	Pv;e [kN/m²]	kh [kN/m³]	Ph;e [kN/m²]	tmax [kN/m²]	dmax [mm]
1	0	3847	917	2693	131	8.07	8
2	0	4191	1968	2934	750	10.88	7
3	0	4528	3130	3169	1354	14.72	7
4	0	4866	4295	3406	2010	18.56	7
5	0	5195	5423	3636	2675	22.28	7
6	0	5357	6120	3750	3095	24.58	7
7	0	5383	6294	3768	3201	25.15	7
8	0	5383	6294	3768	3201	25.15	7
9	0	5383	6294	3768	3201	25.15	7
10	0	5383	6294	3768	3201	25.15	7
11	0	5383	6294	3768	3201	25.15	7
12	0	5383	6294	3768	3201	25.15	7
13	0	5383	6294	3768	3201	25.15	7
14	0	5357	6120	3750	3095	24.58	7
15	0	5195	5423	3636	2675	22.28	7
16	0	4866	4295	3406	2010	18.56	7
17	0	4528	3130	3169	1354	14.72	7
18	0	4191	1968	2934	750	10.88	7
19	0	3847	917	2693	131	8.07	8

Figure 21.8: *Report window, Soil Mechanical Parameters*

22 Design of a pipeline

D-GEO PIPELINE can be used for designing a pipeline using four different techniques:

- ◇ the HDD technique (section 22.1)
- ◇ the micro-tunneling technique (section 22.2)
- ◇ the trench technique (section 22.3)
- ◇ the direct pipe method (section 22.4)

22.1 Design of a pipeline crossing using the HDD technique

The horizontal directional drilling technique is used to install pipelines. A pipe is installed from one point in a geometry with soil materials to another by means of horizontal directional drilling. D-GEO PIPELINE can be used for the design of pipelines or the assessment of preliminary designs of pipelines constructed by means of horizontal directional drilling. Calculations are based on the pipeline configuration, the drill pipe and borehole dimensions and the drilling fluid data. D-GEO PIPELINE calculates the maximum allowable drilling fluid pressure and the minimum drilling fluid pressure at user-specified calculation verticals.

The configuration of a proposed pipeline that has to cross an object is determined by:

- ◇ the location of the entry and exit points (section 22.1.1)
- ◇ the entry and exit angles (section 22.1.2)
- ◇ the limitations of the object to be crossed, specified by the owner of the objects concerned (section 22.1.3)
- ◇ the minimum value of curve radius (section 22.1.4)
- ◇ the value of the combined bending radius (section 22.1.5)

22.1.1 Location of entry and exit points

The entry point is the location where the drilling rig is positioned during the pilot drilling. The exit point is located at the other side of the object that has to be crossed. When the locations of the entry and exit points are determined, it must be taken into account that a minimum distance is required to the object in order to cross the object at a sufficient depth.

22.1.2 Inclination at the entry and exit points

The magnitude of the entry and exit angle is usually between 6°and 15°. The angle can be larger for small drilling rigs. The greater the bending stiffness of the pipeline is, the smaller the entry and exit angles are. Before starting to drill the curved parts of the drilling line, the first 30 to 40 m (3 to 4 drill pipes) must be drilled in a straight line. The magnitude of the exit angle influences the pull-back operation of the pipe through the borehole. The larger the exit angle, the higher the pipeline has to be lifted in order to pull it into the borehole. A small exit angle increases the risk that a blow-out will occur.

22.1.3 The limitations of the object to be crossed

The owner or manager of the object to be crossed may have certain requirements with regard to the crossing depth of the pipeline. Such requirements can be related to the presence of sheet piles or foundation piles. Another reason for special requirements can involve the building plans of structures on piles. Such points are boundary conditions for preparing the pipeline configuration.

22.1.4 Determination of allowable curve radius

The borehole containing a pipeline is usually characterized by an upward and a downward curve. Sometimes a horizontal or combined radius forms part of the drilling line. The smallest possible radius of such a curve depends on the bending stiffness and the yield stress of the pipeline or the drill pipes. For pipes with a relatively small bending stiffness, such as PE pipes, the stiffness of the drill pipes is often the determining factor for the minimum radius of curved sections in the drilling line.

Allowable curve radius for steel pipes

The design radius should be checked for strength:

$$R \geq \frac{\gamma \times E_{\text{b}}}{R_{\text{eb}}} \times \frac{D_{\text{o}}}{2} \tag{22.1}$$

where:

E_{b} is the modulus of elasticity of the pipe material, in kN/m^2;
D_{o} is the outer diameter of the pipe, in m;
γ is the partial safety factor for the bending moment;
R_{eb} is the minimum specified yield strength, in kN/m^2.

(For a pipeline with the following properties: E_{b} = 210000 N/mm^2; R_{eb} = 240 N/mm^2; γ = 1.1, about half the strength of the steel is available for bending stresses, while the remaining half is used for stresses due to pulling force, internal pressure, etc. . .)

The design radius R for steel pipes should also be checked for soil reaction pressure due to bending, according to article E.1.4 of NEN 3650-1:

$$R \geq 1000 \times D_{\text{o}} \qquad \text{for small pipe diameter } (D_{\text{o}} \leq 0.4 \text{ m}) \tag{22.2}$$

$$R \geq C \times \sqrt{D_{\text{o}} \times d_{\text{n}}} \qquad \text{for large pipe diameter } (D_{\text{o}} > 0.4 \text{ m}) \tag{22.3}$$

where C is a constant (without dimension) depending on the soil type as shown in Table 22.2.

Table 22.2: *Values of constant C (according to table E.1 of NEN 3650-1)*

Soil type	*C* [-]
Dense packed sand	8500
Moderate packed sand	9400
Loose packed sand	10200
Stiff Clay	10500
Medium stiff clay	11500
Soft clay and Peat	12500

In D-GEO PIPELINE, the soil type is a function of the cohesion and the friction angle of the soil, as shown in Table 22.3.

Table 22.3: Soil type as a function of the cohesion and the friction angle

Soil type	φ [°]	c [kN/m^2]	Constant C [-]
Dense sand	$\varphi > 32.5$	$c \leq 0.5$	8500
Medium dense sand	$\varphi > 32.5$	$c > 0.5$	9400
Medium dense sand	$30 < \varphi \leq 32.5$		9400
Loose sand	$25 < \varphi \leq 30$	$c \leq 1$	10200
Stiff sandy clay	$25 < \varphi \leq 30$	$c > 1$	10500
Stiff sandy clay	$22.5 < \varphi \leq 25$	$c > 5$	10200
Clayey sand	$22.5 < \varphi \leq 25$	$c \leq 5$	10500
Stiff clay	$20 < \varphi \leq 22.5$	$c > 10$	10500
Medium stiff clay	$20 < \varphi \leq 22.5$	$c \leq 10$	11500
Stiff clay	$17 < \varphi \leq 20$	$c > 10$	10500
Medium stiff clay	$17 < \varphi \leq 20$	$5 < c \leq 10$	11500
Soft clay	$17 < \varphi \leq 20$	$c \leq 5$	12500
Peat /organic clay	$\varphi \leq 17$		12500

In the case of a layered sub-soil, the highest C-value of a layer with a significant thickness is normative. In the case of a sub-soil with an alternation of layers with relative small thicknesses, a weighted interpolation can be performed to determine the C-value:

$$C_{\text{d}} = \sum_{\text{i}=1}^{\text{n}} \left[C_{\text{i}} \times \frac{d_{\text{i}}}{d_{\text{total}}} \right] \quad \text{with} \quad d_{\text{total}} = \sum_{\text{i}=1}^{\text{n}} d_{\text{i}} \tag{22.4}$$

where:

n	is the total number of layers in the curve;
C_{i}	is the C-value of layer i;
d_{i}	is the thickness of layer i, in m;
d_{total}	is the total thickness of all layers in the curve, in m.

Allowable curve radius for polyethylene pipes

According to article 8.6.4 of NEN 3650-3 (NEN, 2012c), the minimal curve-radius for PE pipes is equal to the bending factor as given in Table 22.5 times the diameter.

Table 22.5: Bending factor (acc. to table 6 of NEN 3650-3)

Diameter in mm	Bending factor
63 $\rightarrow$ 160	50
200 $\rightarrow$ 250	75
315 $\rightarrow$ 355	100
400 $\rightarrow$ 630	100
710 $\rightarrow$ 800	125

22.1.5 Determination of combined bending radius

In case the horizontal bending radius coincides with part of a vertical bending radius, a combined 3-dimensional bending radius is formed. For the design of the horizontal directional drilling line, the pull back force and the strength calculation it is necessary to determine the value of the 3-dimensional bending radius. This value can be determined as follows:

$$R_{\text{combi}} = \sqrt{\frac{R_{\text{h}}^2 \times R_{\text{v}}^2}{R_{\text{h}}^2 + R_{\text{v}}^2}} \tag{22.5}$$

where:

R_{combi}	is the combined bending radius, in m;
R_{h}	is the horizontal bending radius, in m;
R_{v}	is the vertical bending radius, in m.

22.2 Design of a pipeline crossing using the micro tunneling technique

The micro tunneling technique is often used for installation of pipelines and small tunnels in densely populated areas. Micro tunneling usually starts horizontal at a certain level below the surface in a so-called launch shaft. The pipe segments included in the micro tunneling machine are placed behind the tunneling machine and pushed in the direction of the reception shaft by means of a jacking frame (Figure 22.1).

The so-called thrust force which has to be provided by the jacking frame is an important parameter in the design of tunnels and pipelines installed by means of micro tunneling. Of course the jacking frame must be able to produce this force.

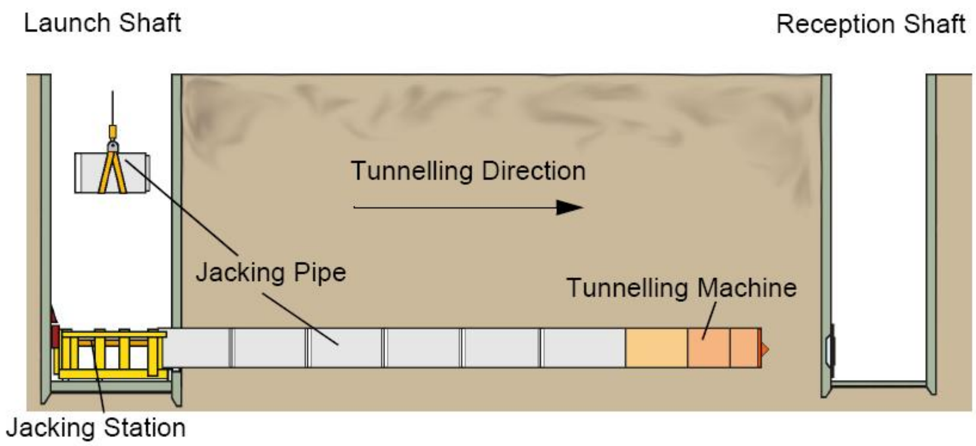


Figure 22.1: *Launch and reception shafts of the micro tunneling machine*

22.3 Design of a pipeline using a trench

Very often, under normal circumstances, pipelines are installed in an excavated trench. In the not very densely populated areas such as agricultural areas and not developed areas, the slopes of the trenches can often be excavated under.

The main risk associated with trenching is instability of the slopes of the trench. This risk is can not be considered in D-GEO PIPELINE. Use of other computer programs such as D-GEO STABILITY is recommended to evaluate this risk.

22.4 Design of a pipeline using the direct pipe method

The Direct Pipe method enables to lay a prefabricated pipeline in one single, continuous working operation into the ground with the aid of the thrust unit, the Pipe Thruster. As with Pipe Jacking, earth excavation is executed by means of a navigable microtunnelling machine, which is directly coupled with the pipeline. The tunnel face is slurry supported; a bentonite suspension is often used for a controlled excavation of the soil.

23 Calculation of soil mechanical data

This section includes background information on the calculation of:

- ◇ neutral vertical stress (section 23.1)
- ◇ passive vertical stress (section 23.2)
- ◇ reduced vertical stress (section 23.3)
- ◇ actual vertical stress (section 23.4)
- ◇ neutral horizontal stress (section 23.5)
- ◇ vertical modulus of subgrade reaction (section 23.6)
- ◇ horizontal modulus of subgrade reaction (section 23.7)
- ◇ ultimate vertical bearing capacity (section 23.8)
- ◇ ultimate horizontal bearing capacity (section 23.9)
- ◇ vertical displacement (section 23.10)
- ◇ maximal axial friction and friction displacement (section 23.11)
- ◇ displacement at maximal friction (section 23.12)
- ◇ global determination of the soil type (section 23.13)
- ◇ traffic load (section 23.14)

If the definition of some parameters in the equations of this chapter is missing, refer to section 1.7.

23.1 Neutral vertical stress

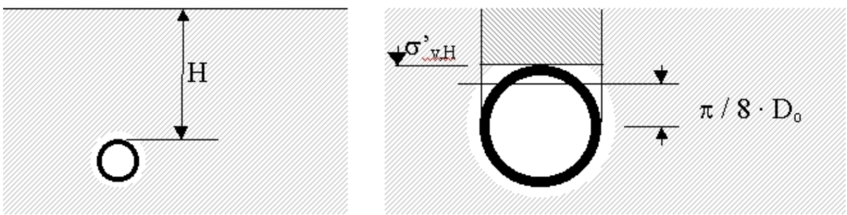


Figure 23.1: *Schematic diagram for calculation of the neutral vertical stress*

According to article C.4.2.2 of NEN 3650-1 (NEN, 2012a), the neutral vertical stress q_n is defined as (Figure 23.1):

$$q_\mathrm{n} = \sigma'_\mathrm{v}\left(H\right) + \left(0.5 - \pi/8\right) \times \gamma' \times D_\mathrm{o} \tag{23.1}$$

where:

$\sigma'_\mathrm{v}\left(H\right)$	is the vertical effective stress at depth H, in kN/m^2: $\sigma'_\mathrm{v}\left(H\right) = \gamma_\mathrm{unsat} \times H_1 + \left(\gamma_\mathrm{sat} - \gamma_\mathrm{w}\right) \times H_2$ (see Figure 23.2 for the definition of H_1 and H_2).
H	is the soil cover above the top of the pipe, in m (see Figure 23.2).
γ'	is the effective unit weight of the soil, in kN/m^3: $\gamma' = \gamma_\mathrm{unsat}$ above the phreatic line and $\gamma' = \gamma_\mathrm{sat} - \gamma_\mathrm{w}$ below the phreatic line.

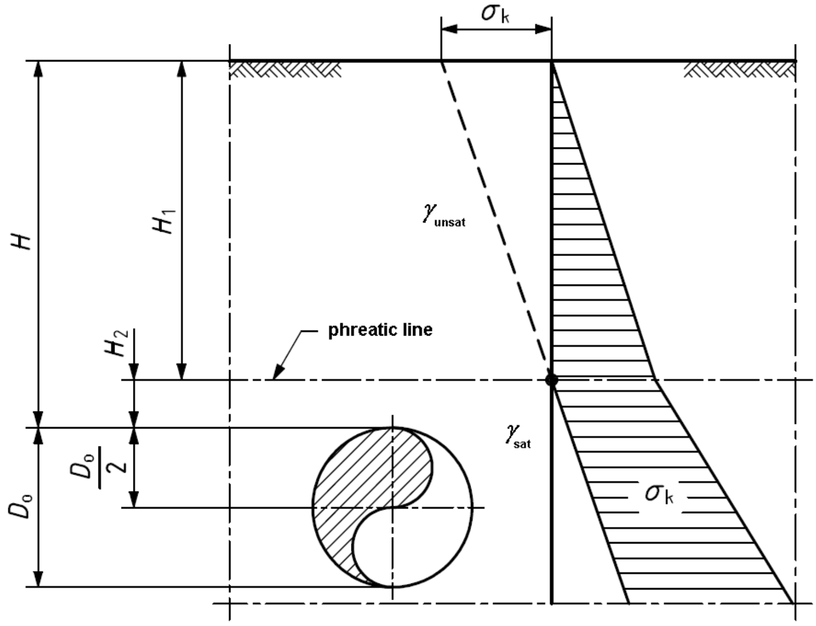


Figure 23.2: *Schematic diagram for the definition of parameters H_1, H_2, γ_{unsat} and γ_{sat} (Figure C.5 of NEN 3650-1)*

23.2 Passive vertical stress

According to article C.4.2.4.2 of NEN 3650-1, the passive vertical stress q_{p} is defined as:

$$q_{\mathsf{p}} = q_{\mathsf{n}} \times \left(1 + 0.3\,\frac{H}{D_{\mathsf{o}}}\right) \leq p'_{\mathsf{max}} \tag{23.2}$$

with:

$$p'_{\mathsf{max}} = (p'_{\mathsf{f}} + c \times \cot\varphi) \times \left[\left(\frac{0.5 \times D_{\mathsf{o}}}{0.5 \times D_{\mathsf{o}} + H}\right)^2 + q\right]^{\frac{-\sin\varphi}{1+\sin\varphi}} - c \times \cot\varphi \tag{23.3}$$

where:

p'_{max}	is the maximum passive vertical stress, in kN/m^2;
p'_{f}	is $\sigma'_0\,(1 + \sin\varphi) + c \times \cos\varphi$, in kN/m^2;
q	is $(\sigma'_0 \times \sin\varphi + c \times \cos\varphi)\,/G$, in kN/m^2;
σ_0'	is the effective isotrope stress, in kN/m^2: $\sigma'_0 = (\sigma'_{\mathsf{v}} + \sigma_{\mathsf{h}})$/2;
$\sigma_{\mathsf{v,h}}$'	is the vertical respectively horizontal effective stress;
c, φ, G	are the soil parameters at the pipe center.

23.3 Reduced neutral vertical stress

In case a drilling technique is used for the installation of the pipeline, the vertical soil load is reduced due to arching. A pipeline installed using the horizontal directional drilling technique is loaded by a strongly reduced soil loads due to arching. For micro tunneling the effect of arching on the soil load is calculated by D-GEO PIPELINE as well. Due to the relative small borehole arching is not completely developed. The relatively small available strain yields incomplete mobilization of the shear strength. The soil load in case of micro tunneling should therefore be calculated using half the value of the angle of internal friction.

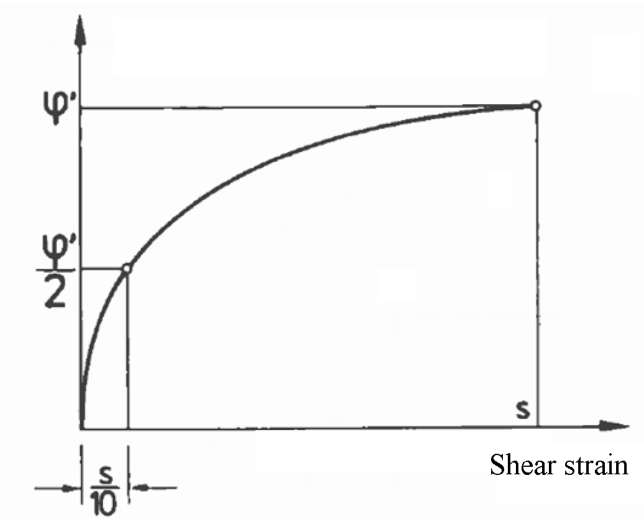


Figure 23.3: *The mobilization of the angle of internal friction in the development of the arching mechanism*

23.3.1 Reduced neutral vertical stress in compressible soil layers

According to article C.4.8.3 of NEN 3650-1 (NEN, 2012a), in compressible soil layers (i.e. clay and peat), the reduced neutral vertical stress $q_{\text{n,r}}$ is defined as:

$$q_{\text{n,r}} = \begin{cases} h \times \gamma' - F_{\text{r}}/2B_1 & \text{if } z > 8B_1 \\ q_{\text{n}} & \text{if } z \leq 8B_1 \end{cases} \tag{23.4}$$

with:

$$F_{\text{r}} = \frac{0.9\,F_{\text{max}}}{1 + \frac{B_1 \times (3H - 2h) \times \alpha}{2C \times H \left(\delta_{\text{d}} + \frac{F_{\text{max}}}{2B_1 \times k_{\text{v;drill fluid}}}\right)}} \tag{23.5}$$

$$F_{\text{max}} = 2B_1 \times (h \times \gamma' - q_{\text{n,r1}}) \tag{23.6}$$

$$q_{\text{n,r1}} = \frac{B_1 \times \left(\gamma' - \frac{c}{B_1}\right)}{K \times \tan\varphi} \times \left[1 - \exp\left(\frac{-K \times \tan\varphi \times h}{B_1}\right)\right] \tag{23.7}$$

where:

B_1	is the half width of the covered ground column, in m: $B_1 = 0.5D_{\text{o}} + D_{\text{o}} \times \tan(45^\circ - \varphi_{\text{b}}/2) \geq R$;
φ_{b}	is the average friction angle over the height of the borehole, in degree;
h	is the soil cover above the borehole, in m (see Figure 23.4);
c, φ, γ'	are the average soil parameters between the surface and the pipe center;
F_{r}	is the permanent friction due to arching effect, in kN/m^2:

F_{max} is the maximal adhesion, in kN/m^2;
$q_{\text{n,r1}}$ is the reduced neutral vertical stress on the pipe, in kN/m^2;
H is the thickness of the compressible layers, in m (see Figure 23.4);
α is a dimensionless factor: $\alpha = \ln(h/h_{\text{ref}})$ with h_{ref} = 1 m;

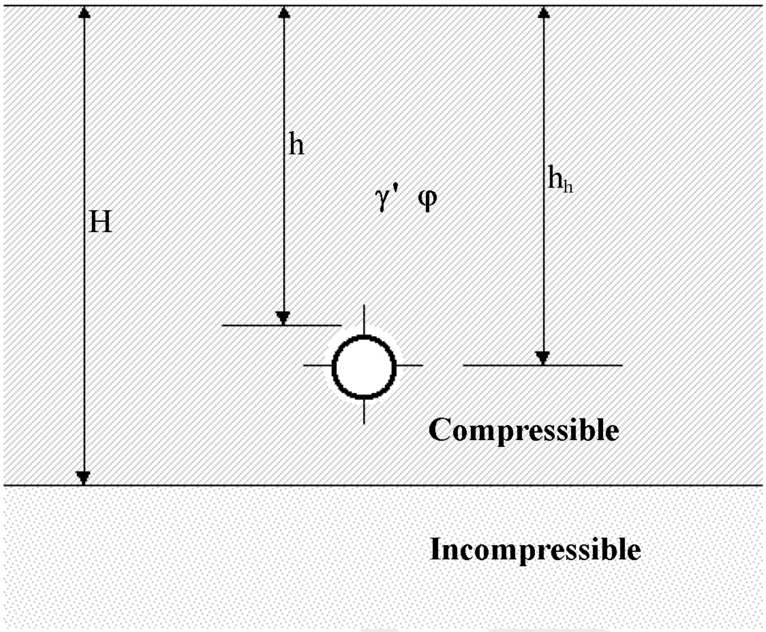


Figure 23.4: *Definitions of H, h and h_h*

23.3.2 Reduced neutral vertical stress in non-compressible soil layers

According to articles C.4.8.3 and C.4.8.4 of NEN 3650-1 (NEN, 2012a), in incompressible soil layers (i.e. sand) situated below compressible soil layers, the reduced neutral vertical stress $q_{\text{n,r}}$ is defined as (if $h > 8B_1$):

$$q_{\text{n,r}} = \frac{B_1 \times \gamma'}{K \times \tan\varphi}\left[1 - \exp\left(\frac{-K \cdot \tan\varphi \cdot h_{\text{p}}}{B_1}\right)\right] + \sigma_{\text{c}} \; \exp\left(\frac{-K \times \tan\varphi \times h_{\text{p}}}{B_1}\right) \tag{23.8}$$

where:

γ' is the average effective unit weight of the soil between the compressibility border and the pipe center, in kN/m^3;
h_{p} is the soil cover above the borehole in the incompressible layers (see Figure 23.5), in m;
φ is the average friction angle between the compressibility border and the pipe center, in degrees;
σ_{c} is the vertical effective stress at the compressibility border, in kN/m^2 (see Figure 23.5).

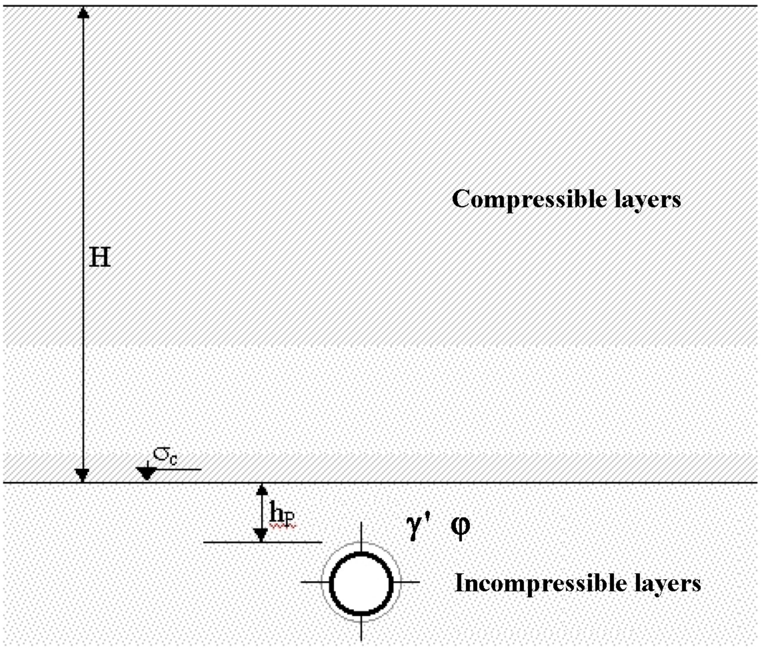


Figure 23.5: *Schematic diagram of H and h_p*

If $h_{\text{p}} < 8B_1$, Equation 23.8 is not applicable for the determination of $q_{\text{n,r}}$. In such case, the following applies:

1) $0 < h_{\text{p}} < 2B_1$: $q_{\text{n,r}}$ is constant and equal to $q_{\text{n,r}}$-border, see section 23.3.1;
2) $2B_1 \leq h_{\text{p}} \leq 4B_1$: interpolation between $q_{\text{n,r}}$-border and $q_{\text{n,r}}$-incompressible for $h_{\text{p}} = 4B_1$;
3) $h_{\text{p}} \geq 4B_1$: $q_{\text{n,r}}$-incompressible as a function of h_{p}.

If $q_{\text{n,r}}$-incompressible ($h_{\text{p}} = 4B_1$) is larger than $q_{\text{n,r}}$-border, then 1) is prescribed and 2) is applicable for $0 < h_{\text{p}} < 4B_1$.

23.4 Initial vertical stress

According to article C.4.2.3 of NEN 3650-1 (NEN, 2012a), the initial vertical stress q_{k} (also called actual vertical stress) for construction in trench is defined as:

$$q_{\text{k}} = q_{\text{n}} + k_{\text{v,tot}} \times \mu \times D_{\text{o}} \leq q_{\text{p}} \tag{23.9}$$

with:

$$\frac{1}{k_{\text{v,tot}}} = \frac{1}{k_{\text{v,top}}} + \frac{1}{k_{\text{v,pipe}}} + \frac{1}{k_{\text{v,bottom}}} \tag{23.10}$$

$$k_{\text{v,pipe}} = \frac{EI_{\text{w}}}{k_{\text{y}} \times D_{\text{o}} \times D_{\text{g}}^3} \tag{23.11}$$

where:

q_{n}	is the neutral vertical stress of the soil, in kN/m^2, see Equation 23.1;
q_{p}	is the passive vertical stress of the soil, in kN/m^2, see Equation 23.2;
$k_{\text{v,tot}}$	is the vertical modulus of subgrade reaction upward, in kN/m^3, see Equation 23.15;

$k_{\text{v,bottom}}$ is the minimum vertical modulus of subgrade reaction downward, in kN/m^3, calculated according to section 23.6.2;
$k_{\text{v,pipe}}$ is the vertical modulus of subgrade reaction of the pipe, in kN/m^3;
μ is the percentage of compaction depending on the type of fill and type of compaction as shown in Table 23.7.

Table 23.7: *Values of parameter μ according to NEN 3650-1*

Compaction	**Type of fill**		
	Soft soil	Stiff clay	Sand
Poorly	0.20	0.15	0.075
Well	0.10	0.075	0.02

23.5 Neutral horizontal stress

23.5.1 Pipelines installed using the HDD technique

According to article C.4.8.6 of NEN 3650-1, the neutral reduced horizontal soil load $q_{\text{h,r}}$ for a pipeline installed using the horizontal drilling technique can be calculated using the following equation:

$$q_{\text{h,r}} = q_{\text{n,r}} \times (1 - \sin \varphi_{\text{df}}) \tag{23.12}$$

where:

$q_{\text{n,r}}$ is the reduced neutral vertical stress of the soil, in kN/m^2, as calculated in section 23.3;
φ_{df} is the angle of internal friction of the drilling fluid, as defined in the *Engineering Data* window (section 4.6.3.1). The default value is 15°.

23.5.2 Pipelines installed in a trench or using micro tunneling

The neutral horizontal soil load $q_{\text{h,n}}$ for a pipeline installed in a trench or using the micro tunneling technique can be calculated using the following equation:

$$q_{\text{h,n}} = q_{\text{n}} \times (1 - \sin \varphi_{\text{b}}) \tag{23.13}$$

where:

q_{n} is the neutral vertical stress of the soil, in kN/m^2, as calculated in Equation 23.1 in section 23.1;
φ_{b} is the average angle of internal friction of the soil over the height of the borehole.

In micro tunneling the space in between the pipeline or tunnel is usually relatively small, moreover the space in between the bore hole wall and the pipeline or tunnel is often filled with grout after installation.

23.6 Vertical modulus of subgrade reaction

Due to the soil-pipe interaction, induced by either the pipe or the soil, soil deformations and pipe displacement will occur. The deformations lead to increase or decrease of the soil load on the pipe. This soil reaction behavior is modeled by using a spring model. By locating springs around the pipe, the displacement and related stress changes can be calculated (Figure 23.6). The increase or decrease of the soil reaction stress is usually calculated by linear or bi-linear springs. The stiffness of the spring is expressed as a modulus of subgrade reaction.

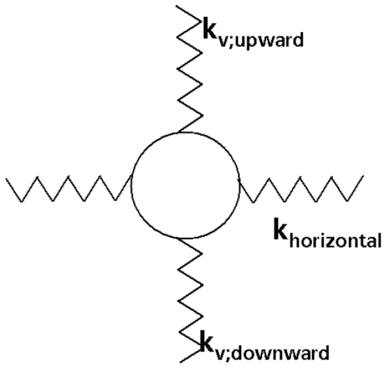


Figure 23.6: *Pipe soil interaction modeled by springs*

Since the soil-pipe interaction is influenced by the installation method, different calculation methods to determine the moduli of subgrade reaction exist:

- ◇ For installation using a drilling technique (HDD or micro tunneling), refer to section 23.6.1;
- ◇ For Installation in a trench, refer to section 23.6.2;

23.6.1 Pipelines installed using a drilling technique

According to article C.4.3.3 c) of NEN 3650-1, the stiffness of the spring below ($k_{\text{v,bottom}}$) and above the pipe ($k_{\text{v,top}}$) is:

$$k_{\text{v}} = \frac{f_{\text{E}} \times E}{m \times (1 - \nu^2) \times \sqrt{A}} \tag{23.14}$$

with:

$$m = \frac{52.31 + \ell/b}{51.90 + 3.596 \times \ell/b}$$
$$\ell = \pi/\lambda$$
$$\lambda = \sqrt[4]{k_{\text{v}} \times f_{\text{kv}} \times \frac{D_{\text{o}}}{4\ E_{\text{b}} \times I_{\text{b}}}}$$

where:

E, ν	are the average parameters of the soil along a distance of 5 D_{o} above the top of the pipeline for $k_{v,top}$ and below the bottom of the pipeline for $k_{v,bottom}$;
A	is $\ell \times b$ = support area, in m^2;
b	is the minimum support width, in m: $b = D_{\text{o}}$;
ℓ	is the minimum support length, in m;
λ	is the characteristic stiffness pipeline-soil, in m^{-1};

I_{b}	is the moment of inertia of the pipeline, in m^4: $I_{\text{b}} = \frac{\pi}{64}\left[D_{\text{o}}^4 - (D_{\text{o}} - 2d_{\text{n}})^4\right]$
m	is the shape coefficient, depending on ℓ/b.

23.6.2 Pipelines installed in a trench

Vertical modulus of subgrade reaction upward

According to article C.4.3.2 of NEN 3650-1, the vertical modulus of subgrade reaction upward are:

$$ {}_{\text{v,top}} = \frac{q_{\text{p}} - q_{\text{n}}}{z_{\text{max}}} \tag{23.15}$$

$$ k_{\text{v,top,max}} = \frac{q_{\text{p}}}{z_{\text{max}}} \tag{23.16}$$

with:

$$ z_{\text{max}} = \frac{0.25 \times D_{\text{o}}}{E^{1.5} \times \sqrt{\frac{H}{D_{\text{o}}}}} \quad \text{for clay and peat} \tag{23.17}$$

$$ z_{\text{max}} = \frac{0.20 \times D_{\text{o}}}{E^{0.5} \times \sqrt{\frac{H}{D_{\text{o}}}}} \quad \text{for sand} \tag{23.18}$$

where:

q_{p}	is the passive vertical soil load, see Equation 23.2;
q_{n}	is the neutral vertical soil load, see Equation 23.1;
z_{max}	is the maximum displacement, in m;
E	is the average Young's modulus of the soil along a distance of 5 D_{o} above the top of the pipeline, in MPa;
H	is the soil cover above the top of the pipe, in m.

Vertical modulus of subgrade reaction downward

The vertical modulus of subgrade reaction downward is characterized by a bi-linear spring. $k_{\text{v,1}}$ is the modulus of subgrade reaction in between 0 and 2/3 of the vertical bearing capacity, while $k_{\text{v,2}}$ is the modulus of subgrade reaction in between 2/3 of the vertical bearing capacity and the vertical bearing capacity.

For clay and peat, the modules of subgrade reaction downward are:

$$ k_{\text{v,1}} = 0.25 \times c_{\text{u}} \times \frac{P_{\text{we}}}{D_{\text{o}}} \tag{23.19}$$

$$ k_{\text{v,2}} = 0.04 \times c_{\text{u}} \times \frac{P_{\text{we}}}{D_{\text{o}}} \tag{23.20}$$

For sand, the modules of subgrade reaction downward are:

$$ k_{\text{v,1}} = 0.5 \times E \times \frac{P_{\text{we}}}{D_{\text{o}}} \tag{23.21}$$

$$ k_{\text{v,2}} = 0.1 \times E \times \frac{P_{\text{we}}}{D_{\text{o}}} \tag{23.22}$$

where c_{u} and E (in kN/m^2 respectively MN/m^2) are the average parameters of the soil along a distance of 5 D_{o} below the bottom of the pipeline and P_{we} is the vertical bearing capacity determined according to section 23.8.

If c_{u} is nil, a fictive undrained cohesion is used by the program:

$$c_{\text{u,fictive}} = \frac{1}{2} (1 + K_0) \times \sigma'_{\text{h}} \times \sin\varphi + c \times \cos\varphi \tag{23.23}$$

23.7 Horizontal modulus of subgrade reaction

23.7.1 Pipelines installed using a drilling technique

The horizontal modulus of subgrade reaction is:

$$k_{\text{h}} = 0.7\, k_{\text{v,bottom}} \tag{23.24}$$

where $k_{\text{v,bottom}}$ is the vertical modulus of subgrade reaction at the bottom of the pipe as determined in Equation 23.14.

23.7.2 Pipelines installed in a trench

According to article C.4.3.4.1 of NEN 3650-1, the horizontal modulus of subgrade reaction upward is:

$$k_{\text{h}} = \frac{q_{\text{he}}}{y_{\text{max}}} \times \frac{(1 - 0.3 \times B)}{A} \tag{23.25}$$

where:

q_{he}	is the ultimate horizontal bearing capacity, see Equation 23.29;
y_{max}	is the maximal displacement, in m: $y_{\text{max}} = D_{\text{o}} \times \left[0.05 + 0.03 \times \left(\frac{Z}{D_{\text{o}}} + 0.5\right)\right]$
A	is a constant (A = 0.145);
B	is a constant (B = 0.855).

23.8 Ultimate vertical bearing capacity

According to article C.4.4.2 of NEN 3650-1 (NEN, 2012a), the ultimate vertical bearing capacity is:

$$P_{\text{we}} = 0.95 \left[0.5\, \gamma'\, B\, N_\gamma\, S_\gamma\, d_\gamma + S_{\text{q}}\, N_{\text{q}}\, d_{\text{q}}\, (q_{\text{n}} + c \times \cot\varphi) - c \times \cot\varphi\right] \tag{23.26}$$

where:

c, φ, γ'	are the average soil parameters along the sliding plane;
B	is the width of the foundation element, in m (for pipeline: $B = D_{\text{o}}$);
Z	is the depth until the pipe, in m: $Z = H + D_{\text{o}}/2$;
H	is the soil cover above the pipe, in m;
L	is the length of the foundation element, in m: $L = 10\, B$;
N_γ	is the bearing capacity factor for the effect of the effective weight of the soil under the foundation surface: $N_\gamma = 1.5 \times (N_{\text{q}} - 1) \times \tan\varphi$
s_γ	is the shape factor for the effect of effective weight of the soil under the foundation surface: $s_\gamma = 1 - 0.4B/L$;
d_γ	is the depth factor for the effect of the effective weight (d_γ = 1);

N_q is the bearing capacity factor for the effect of the soil cover: $N_\mathsf{q} = \exp^{\pi \times \tan\varphi} \times \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)$;
s_q is the shape factor for the effect of soil cover: $s_\mathsf{q} = 1 + \sin \times B/L$;
d_q is the depth factor for the effect of the soil cover: $d_\mathsf{q} = 1 + 2\tan\varphi\,(1-\sin\varphi)^2 \arctan(Z/B)$.

If φ = 0, the ultimate vertical bearing capacity is:

$$P_\mathsf{we} = 0.95\left[\sigma'_\mathsf{v} + c\ (\pi+2) \times (1 + s_\mathsf{c} + d_\mathsf{c})\right] \tag{23.27}$$

where:

s_c is the shape factor for the effect of cohesion: $s_\mathsf{c} = 0.2B/L = 0.02$;
d_c is the depth factor for the effect of cohesion: $d_\mathsf{c} = 0.4\arctan(Z/B)$.

23.9 Ultimate horizontal bearing capacity

23.9.1 Pipelines installed using the HDD technique

The horizontal bearing capacity q_{he} is of equal magnitude as the maximum vertical passive soil load p'_max (see Equation 23.3) and is therefore defined as:

$$q_\mathsf{he} = p'_\mathsf{max} = (p'_\mathsf{f} + c \times \cot\varphi) \times \left[\left(\frac{0.5\ D_\mathsf{o}}{0.5\ D_\mathsf{o} + H}\right)^2 + q\right]^{\frac{-\sin\varphi}{1+\sin\varphi}} - c \times \cot\varphi \tag{23.28}$$

Refer to section 23.2 for the definition of the parameters.

Similar to the determination of the maximum vertical passive soil load, for shallow depth of the pipeline ($H < 5D_\mathsf{o}$) the soil load should be calculated according the formula for the horizontal bearing capacity for trench or micro tunneling.

23.9.2 Pipelines installed in a trench or using micro tunneling

According to article C.4.4.3a, the horizontal bearing capacity q_he of a pipeline in a trench or using the micro tunneling technique is calculated as follows:

$$q_\mathsf{he} = K_\mathsf{q} \times \sigma'_\mathsf{v} + 0.7 \times \alpha \times K_\mathsf{c} \times c \tag{23.29}$$

where:

K_q is the load coefficient according to Brinch Hansen, see Figure 23.7 and Equation 23.30;
K_c is the load coefficient according to Brinch Hansen, see Figure 23.7 and Equation 23.31;
σ'_v is the effective vertical stress at the pipe center, in kN/m^2;
α is a coefficient: α = 0.6 for trench and α = 1 for micro tunneling.

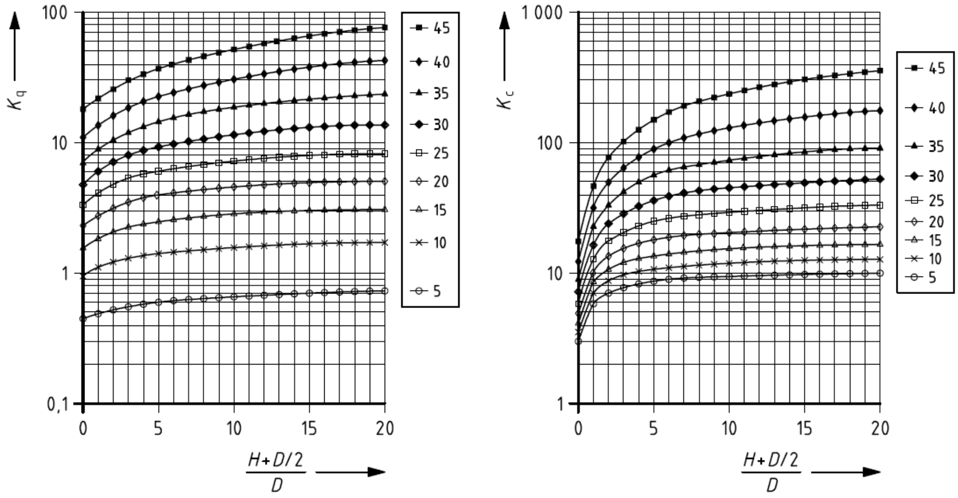


Figure 23.7: *Values K_q and K_c according to Brinch Hansen (Figure C.14 of the NEN 3650-1)*

The angle of internal friction φ and the cohesion c for the calculation of the load coefficients K_q and K_c is determined for the soil layers 2.5 D_o above and 2.5 D_o below the axis of the pipeline. The minimum value is used. According to Brinch Hansen (Brinch Hansen, 1970), the load coefficients are:

$$K_\mathrm{q} = \frac{K_\mathrm{q}^0 + K_\mathrm{q}^\infty \times \alpha_\mathrm{q} \times \frac{D}{B}}{1 + \alpha_\mathrm{q} \times \frac{D}{B}} \tag{23.30}$$

$$K_\mathrm{c} = \frac{K_\mathrm{c}^0 + K_\mathrm{c}^\infty \times \alpha_\mathrm{c} \times \frac{D}{B}}{1 + \alpha_\mathrm{c} \times \frac{D}{B}} \tag{23.31}$$

where:

$$\begin{aligned}
K_\mathrm{q}^0 &= \exp\left[\left(\frac{\pi}{2} + \varphi\right) \times \tan\varphi\right] \times \cos\varphi \times \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \\
&\quad - \exp\left[\left(-\frac{\pi}{2} + \varphi\right) \times \tan\varphi\right] \times \cos\varphi \times \tan\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \\
K_\mathrm{c}^0 &= \left\{\exp\left[\left(\frac{\pi}{2} + \varphi\right) \times \tan\varphi\right] \times \cos\varphi \times \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) - 1\right\} \times \cot\varphi \\
K_\mathrm{q}^\infty &= K_\mathrm{c}^\infty \times K_0 \times \tan\varphi \\
K_\mathrm{c}^\infty &= N_\mathrm{c} \times d_\mathrm{c}^\infty \\
d_\mathrm{c}^\infty &= 1.58 + 4.09 \times \tan^4\varphi \\
N_\mathrm{c} &= \left[\exp\left(\pi \times \tan\varphi\right) \times \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) - 1\right] \times \cot\varphi \\
K_0 &= 1 - \sin\varphi \\
\alpha_\mathrm{q} &= \frac{K_\mathrm{q}^0}{K_\mathrm{q}^\infty - K_\mathrm{q}^0} \times \frac{K_0 \times \sin\varphi}{\sin\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)} \\
\alpha_\mathrm{c} &= \frac{K_\mathrm{c}^0}{K_\mathrm{c}^\infty - K_\mathrm{c}^0} \times 2\sin\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)
\end{aligned}$$

23.10 Vertical displacement

The vertical displacement of the soil layers below the pipeline due to an increased load on these layers can be calculated using the Isotache method or the Koppejan method. In addition to the calculated vertical displacement by D-GEO PIPELINE, a given value for vertical displacement can be entered manually (see section 4.4.2).

23.10.1 Isotache model

Creep Isotaches are lines of equal rate (speed, velocity) of secular (visco-plastic) strain $\varepsilon_{\mathsf{s}}^{\mathsf{H}}$ in a plot of (natural) strain versus (natural) logarithm of vertical effective stress. These are displayed in the Figure 23.8.

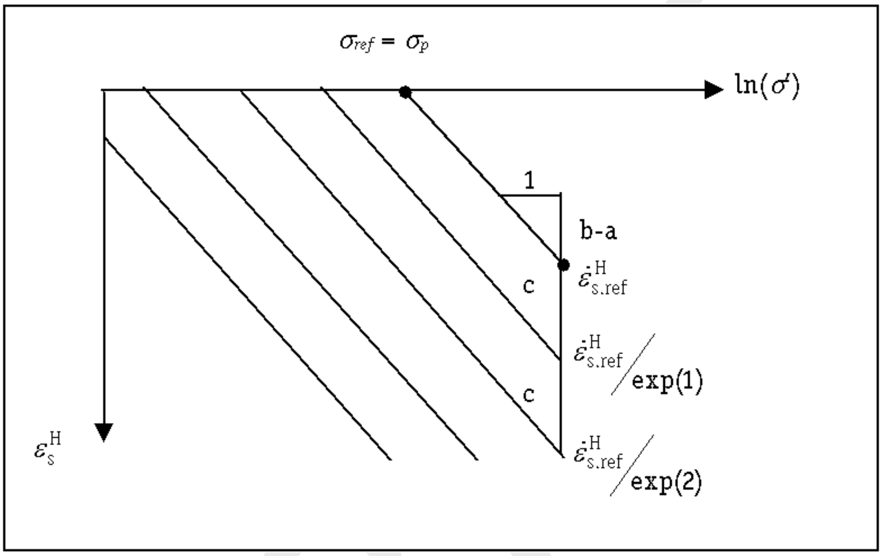


Figure 23.8: *Creep Isotache pattern*

The Isotaches are all parallel with slope $b-a$. The Isotache a parameter determines the direct (elastic) strain component $\varepsilon_{\mathsf{d}}^{\mathsf{H}}$. The b and c parameters determine the secular (visco-plastic) creep component $\varepsilon_{\mathsf{s}}^{\mathsf{H}}$.

$$b - a = \frac{d\varepsilon_{\mathsf{s}}^{\mathsf{H}}}{d\ln\sigma'} \tag{23.32}$$

$$c = -\frac{d\varepsilon_{\mathsf{s}}^{\mathsf{H}}}{d\ln\left(\dot{\varepsilon}_{\mathsf{s}}^{\mathsf{H}}\right)} \tag{23.33}$$

$$a = \frac{d\varepsilon_{\mathsf{d}}^{\mathsf{H}}}{d\ln\sigma'} \tag{23.34}$$

$$\varepsilon^{\mathsf{H}} = \varepsilon_{\mathsf{s}}^{\mathsf{H}} + \varepsilon_{\mathsf{d}}^{\mathsf{H}} \tag{23.35}$$

The reference Isotache starts at pre-consolidation stress $\sigma_{\mathsf{ref}} = \sigma_{\mathsf{p}}$ and is characterized by a reference creep strain rate $\dot{\varepsilon}_{\mathsf{s.ref}}^{\mathsf{H}}$.

The secular creep rate is given by:

$$\dot{\varepsilon}_{\mathsf{s}}^{\mathsf{H}} = \dot{\varepsilon}_{\mathsf{s.ref}}^{\mathsf{H}} \exp\left(\frac{(b-a)\ln\left(\frac{\sigma'}{\sigma_{\mathsf{p}}}\right) - \varepsilon_{\mathsf{s}}^{\mathsf{H}}}{c}\right) \tag{23.36}$$

It can be shown that the secular creep rate is related to a so-called intrinsic time τ, which is related to the common time t by a time shift t_{shift}.

$$\dot{\varepsilon}_{\text{s}}^{\text{H}} = \frac{c}{\tau} \qquad \text{with} \qquad \tau = t - t_{\text{shift}} \tag{23.37}$$

This time shift in fact represents the creep history of the soil.

The total rate of strain is the sum of the elastic and secular rates:

$$\dot{\varepsilon}^{\text{H}} = \dot{\varepsilon}_{\text{s}}^{\text{H}} + \dot{\varepsilon}_{\text{d}}^{\text{H}} \tag{23.38}$$

Time integration of Equation 23.38 finally yields Equation 23.39.

$$\varepsilon^{H} = \; a \ln\left(\frac{\sigma'}{\sigma_0}\right) + c \ln\left[1 \; + \; \int_0^t \left(\frac{\sigma'}{\sigma_{\text{p}}}\right)^{\frac{b-a}{c}} \frac{d\tau}{\tau_0}\right] \tag{23.39}$$

The reference time τ_0 is set by default to 1 day.

$$\tau_0 = 1 \text{ day} \tag{23.40}$$

During a constant stress period after virgin loading, Equation 23.39 simplifies to:

$$\varepsilon^{\text{H}} = a \ln \frac{\sigma_{\text{p}}}{\sigma_0} + b \ln \frac{\sigma'}{\sigma_{\text{p}}} + c \ln \frac{\tau}{\tau_0} \tag{23.41}$$

This equation applies to the creep tail when σ' has become constant, and this is the familiar relation for one-dimensional creep, with strain depending on logarithm of time.

Here, however, apart from using natural strain, the time to use is the intrinsic time τ. This removes the age-old difficulty of defining the origin of time to use in the compression law, e.g. years A.D. (Buisman: dykes of Marken island), time after loading, time after last loading stage, etc.

Figure 23.9 illustrates the effect of the t_{shift} parameter (denoted by t_{r}) on the creep tail.

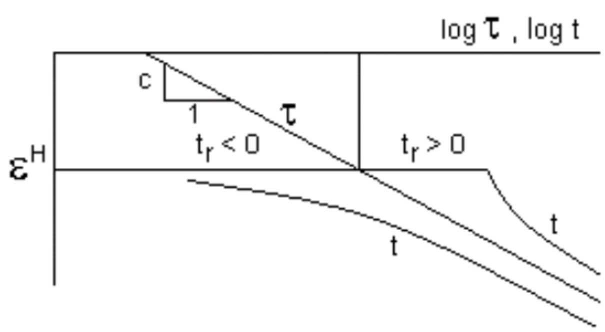


Figure 23.9: *Influence of the $t_{shift} = t_r$ parameter on the creep tail*

While ϵ^H – log t plots can be either steepening or flattening, the ϵ^H – log τ plot is linear. Steepening occurs for relatively small load increments, and is due to changing the origin of time to the start of the new increment. Flattening occurs for relatively large load increments. The linear relationship with intrinsic time therefore allows a more accurately identification and interpretation of the creep tail.

23.10.2 Koppejan model

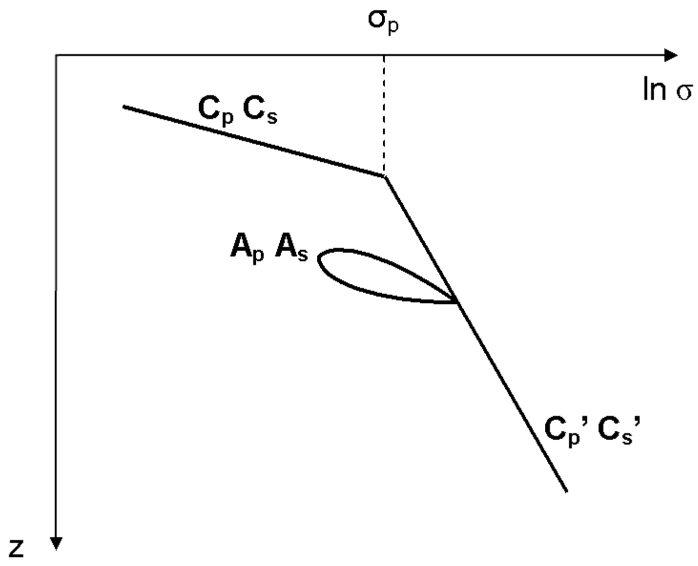


Figure 23.10: Koppejan settlement

Four different situations can be distinguished for Koppejan:

- If the vertical effective stress is smaller than the pre-consolidation pressure, the primary settlement can be calculated from:

$$\frac{\Delta h_{\mathrm{prim}}}{h_0} = \frac{1}{C_{\mathrm{p}}} \ln\left(\frac{\sigma'}{\sigma_0}\right), \sigma_0 < \sigma' < \sigma_{\mathrm{p}} \tag{23.42}$$

- If the vertical effective stress is larger than the pre-consolidation pressure, the primary settlement can be calculated from:

$$\frac{\Delta h_{\mathrm{prim}}}{h_0} = \frac{1}{C_{\mathrm{p}}} \ln\left(\frac{\sigma_{\mathrm{p}}}{\sigma_0}\right) + \frac{1}{C'_{\mathrm{p}}} \ln\left(\frac{\sigma'}{\sigma_0}\right), \sigma_0 < \sigma_{\mathrm{p}} < \sigma' \tag{23.43}$$

- If vertical effective stress is smaller than the pre-consolidation pressure, the secondary settlement for one loading can be calculated from:

$$\frac{\Delta h_{\mathrm{sec}}}{h_0} = \frac{1}{C_{\mathrm{s}}} \log\left(\frac{t}{t_0}\right) \ln\left(\frac{\sigma'}{\sigma_0}\right), \sigma_0 < \sigma' < \sigma_{\mathrm{p}} \tag{23.44}$$

- If the vertical stress is larger than the pre-consolidation pressure, the secondary settlement for one loading can be calculated using Equation 23.45:

$$\frac{\Delta h_{\mathrm{sec}}}{h_0} = \frac{1}{C_{\mathrm{s}}} \log\left(\frac{t}{t_0}\right) \ln\left(\frac{\sigma_{\mathrm{p}}}{\sigma_0}\right) + \frac{1}{C'_{\mathrm{s}}} \log\left(\frac{t}{t_0}\right) \ln\left(\frac{\sigma'}{\sigma_{\mathrm{p}}}\right), \sigma_0 < \sigma_{\mathrm{p}} < \sigma' \tag{23.45}$$

where:

C_{p} is the primary compression coefficient below pre-consolidation pressure;

C_p'	is the primary compression coefficient above pre-consolidation pressure;
C_s	is the secondary compression coefficient below pre-consolidation pressure;
C_s'	is the secondary compression coefficient above pre-consolidation pressure;
Δh_{prim}	is the primary settlement contribution of a layer, in m;
h_0	is the initial layer thickness, in m;
σ_0	is the initial vertical effective stress, in kN/m^2;
σ_p	is the pre-consolidation pressure, in kN/m^2;
Δh_{sec}	is the secondary settlement contribution of a layer, in m;
t	is the time, in days;
t_0	is the reference time, in days.

23.11 Maximal axial friction

The friction between the pipe wall and the surrounding soil depends on the relative displacement between the pipe wall and the soil. When the relative displacement between the soil and the pipe reaches a maximal value, the friction does not increase anymore. The friction depends on:

◇ The stresses around the pipe
◇ The adhesion between the soil and the pipe wall
◇ The roughness of the pipe wall
◇ The angle of friction of the soil

23.11.1 Pipelines installed using the HDD technique

The maximal axial friction along the pipeline can be put in the *Engineering Data* window (section 4.6.3) as parameter f_2 (friction between pipe – drilling fluid). The conditions directly after the installation are considered as critical.

23.11.2 Pipelines installed in a trench or using micro tunneling

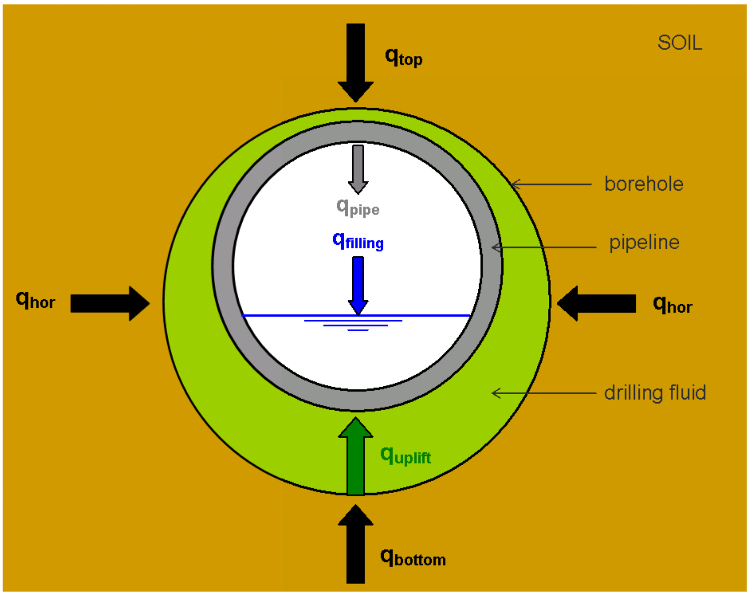


Figure 23.11: *Schematization of the forces acting on the pipe*

The following forces are acting on the pipe (Figure 23.11):

a) **Uplift force**:

$$q_{\text{uplift}} = \frac{\pi}{4} \times D_{\text{o}}^2 \times \gamma_{\text{df}} \tag{23.46}$$

b) **Weight of the pipeline**:

$$q_{\text{pipe}} = \frac{\pi}{4} \times \left(D_{\text{o}}^2 - D_{\text{i}}^2\right) \times \gamma_{\text{b}} \tag{23.47}$$

c) **Weight of the filling (water)**:

$$q_{\text{filling}} = \frac{\pi}{4} \times D_{\text{i}}^2 \times \gamma_{\text{w}} \times P_{\text{w}} \tag{23.48}$$

d) **Stress at the top of the pipe:**

$$q_{\text{top}} = \begin{cases} \max\left[q_{\text{n}}; \min\left(-q_{\text{eff}}; q_{\text{p}}\right)\right] & \text{for trenching} \\ \max\left[q_{\text{n,r}}; \min\left(-q_{\text{eff}}; q_{\text{p}}\right)\right] & \text{for micro tunneling} \end{cases} \tag{23.49}$$

e) **Stress at the bottom of the pipe:**

$$q_{\text{bottom}} = \begin{cases} \max\left(q_{\text{n}} + q_{\text{eff}}; P_{\text{we}}\right) & \text{for trenching} \\ \max\left(q_{\text{n,r}} + q_{\text{eff}}; P_{\text{we}}\right) & \text{for micro tunneling} \end{cases} \tag{23.50}$$

The effective weight of the pipeline is defined as:

$$q_{\text{eff}} = q_{\text{pipe}} + q_{\text{filling}} - q_{\text{uplift}} \tag{23.51}$$

where:

q_{n}	is the neutral vertical stress, see Equation 23.1 in section 23.1;
q_{p}	is the passive vertical stress, see Equation 23.2 in section 23.2;
$q_{\text{n,r}}$	is the reduced neutral vertical stress, see section 23.3;
P_{we}	is the vertical bearing capacity, see Equation 23.26 in section 23.8.

The maximal axial friction along the pipeline is defined as follows:

$$W = W_{\text{top}} + W_{\text{bottom}} + 2W_{\text{hor}} \tag{23.52}$$

with:

$$W_{\text{t}} = \begin{cases} \frac{\pi}{4}\ D_{\text{o}}\ \left(q_{\text{t}} \times \tan\delta_{\text{t}} + 0.6 \times a_{\text{t}}\right) & \text{for trenching} \\ \frac{\pi}{4}\ D_{\text{o}}\ \left(q_{\text{t}} \times \tan\delta_{\text{lub fluid}} + a_{\text{lub fluid}}\right) & \text{for micro tunneling} \end{cases}$$

$$W_{\text{b}} = \begin{cases} \frac{\pi}{4}\ D_{\text{o}}\ \left(q_{\text{b}} \times \tan\delta_{\text{b}} + 0.6 \times a_{\text{b}}\right) & \text{for trenching} \\ \frac{\pi}{4}\ D_{\text{o}}\ \left(q_{\text{b}} \times \tan\delta_{\text{lub fluid}} + a_{\text{lub fluid}}\right) & \text{for micro tunneling} \end{cases}$$

$$W_{\text{hor}} = \begin{cases} \frac{\pi}{4}\ D_{\text{o}}\ \left(K_0 \times \sigma'_{\text{v}} \times \tan\delta_{\text{m}} + 0.6 \times a_{\text{m}}\right) & \text{for trenching} \\ \frac{\pi}{4}\ D_{\text{o}}\ \left(K_{\text{a}} \times \sigma'_{\text{v}} \times \tan\delta_{\text{lub fluid}} + a_{\text{lub fluid}}\right) & \text{for micro tunneling} \end{cases}$$

where:

W	is the maximal friction, in kN/m;
a_{t}, a_{b}, a_{m}	are the adhesion's of the soil at the top, respectively bottom and middle of the pipe, in kN/m^2;

δ_t, δ_b, δ_m	are the delta friction angles of the soil at the top, respectively bottom and middle of the pipe, in radians. For sand, δ can be approximated by 2/3 φ, while in clay and peat the value of the friction angle can be neglected (δ = 0).
$a_{\text{lub fluid}}$	is the adhesion of the lubrification fluid, in kN/m^2, as defined in the *Engineering Data* window (section 4.6.3.2);
$\delta_{\text{lub fluid}}$	is the delta lubrification fluid, in radians, as defined in the *Engineering Data* window (section 4.6.3.2);
K_0	is the neutral earth pressure ratio: $K_0 = 1 - \sin\varphi$;
K_a	is the active earth pressure ratio: $K_a = \left(\frac{\cos\varphi}{1+\sin\varphi}\right)^2$;
φ	is the friction angle of the soil at the middle of the pipe, in radians;
σ_v'	is the effective vertical stress at the middle of the pipe, in kN/m^2.

23.12 Displacement at maximal friction

23.12.1 Pipelines installed using the HDD technique

The displacement necessary to develop the maximal axial friction along the pipeline is estimated between 6 and 9 mm. D-GEO PIPELINE uses an average value of 7.5 mm.

23.12.2 Pipelines installed in a trench or using micro tunneling

The displacement necessary to develop the maximal axial friction along the pipeline is determined using Table 23.19.

Table 23.19: Friction displacement

Soil type	φ [°]	c [kN/m^2]	Friction displacement [mm]
Dense sand	$\varphi > 32.5$	$c \leq 0.5$	1-3
Medium dense sand	$30 < \varphi \leq 32.5$	$c \leq 0.5$	3-5
Stiff clay	$\varphi > 30$	$c > 0.5$	2-4
Loose sand	$25 < \varphi \leq 30$	$c < 1$	5-8
Stiff sandy clay	$25 \leq \varphi \leq 30$	$c \geq 1$	4-6
Clayey sand	$22.5 < \varphi < 25$	$c < 5$	5-8
Stiff sandy clay	$\varphi \geq 22.5$	$c \geq 5$	2-4
Stiff clay	$\varphi > 17$	$c \geq 10$	2-4
Medium stiff clay	$20 < \varphi \leq 22.5$		4-6
Medium stiff clay	$17 \leq \varphi \leq 20$	$c \geq 5$	4-6
Soft clay	$17 \leq \varphi \leq 20$	$c < 5$	6-10
Peat /organic clay	$\varphi < 17$		10-15

23.13 Global determination of the soil type

The global soil type in which the pipeline is installed is used for the determination of safety factors which are required for a pipe stress analysis. The classification of global soil types given in Table 23.20 is applied in D-GEO PIPELINE.

Table 23.20: Classification of the soil type

Global soil type	φ [°]	c [kN/m^2]
Sand	$\varphi > 32.5$	$c \leq 0.5$
Sand	$30 < \varphi \leq 32.5$	$c \leq 0.5$
Clay	$\varphi > 30$	$c > 0.5$
Sand	$25 < \varphi \leq 30$	$c < 1$
Clay	$25 \leq \varphi \leq 30$	$c \geq 1$
Sand	$22.5 < \varphi < 25$	$c < 5$
Clay	$\varphi \geq 22.5$	$c \geq 5$
Clay	$\varphi > 17$	$c \geq 10$
Clay	$20 < \varphi \leq 22.5$	
Clay	$17 \leq \varphi \leq 20$	$c \geq 5$
Clay	$17 \leq \varphi \leq 20$	$c < 5$
Peat	$\varphi < 17$	

23.14 Traffic load

According to C.5.1 of NEN 3650-1 (NEN, 2012a) two load models are considered, depending on the type of road:

- ◇ For dual carriageways and regional roads, 'Load Model 3' (i.e. Graph I) according to EN NEN-1991-2 (this concerns special transports) is assumed;
- ◇ For other roads, the 'Fatigue Load Model 2, Lorry 4' (i.e. Graph II) is assumed according to EN NEN-1991-2 (this load model covers the 'set of frequent lorries' wich can occur on European roads, such as described in EN NEN-1991-2, with exception of the special transports).

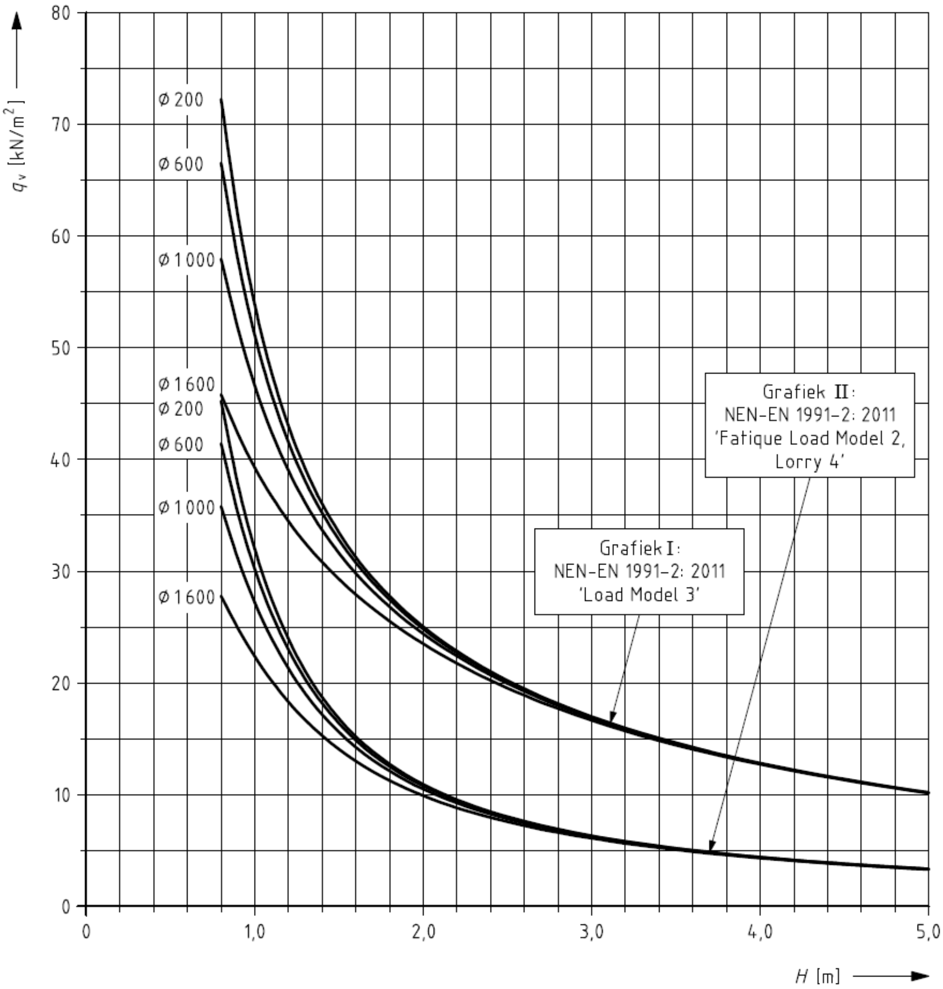


Figure 23.12: *Traffic load as a function of the depth and the pipe diameter, for both load models, according to NEN 3650-1*

For both load models (Graph I and Graph II), the spreading of the traffic load q_v along the depth is given in Figure 23.12 for four pipe diameters: 200, 600, 1000 and 1600 mm. Intermediary diameters are linearly interpolated. D-GEO PIPELINE uses the following formulas to calculate q_v as a function of the depth Z, derived from Figure 23.12:

- For **Graph I**:
  - For ⊘ 200 mm: $q_\text{v} = 53.988 \times Z^{-1.058}$
  - For ⊘ 600 mm: $q_\text{v} = 51.403 \times Z^{-1.016}$
  - For ⊘ 1000 mm: $q_\text{v} = 46.522 \times Z^{-0.94}$
  - For ⊘ 1600 mm: $q_\text{v} = 39.448 \times Z^{-0.804}$
- For **Graph II**:
  - For ⊘ 200 mm: $q_\text{v} = 31.716 \times Z^{-1.457}$
  - For ⊘ 600 mm: $q_\text{v} = 29.501 \times Z^{-1.4}$
  - For ⊘ 1000 mm: $q_\text{v} = 26.776 \times Z^{-1.324}$
  - For ⊘ 1600 mm: $q_\text{v} = 21.963 \times Z^{-1.172}$

24 Drilling fluid pressures calculation

This section includes background information on the calculation of the following drilling fluid pressures:

- ◇ Minimum required drilling fluid pressure (section 24.1)
- ◇ Maximum allowable drilling fluid pressure (section 24.2)

24.1 Minimum required drilling fluid pressure

Drilling fluid consists of a mixture of water and bentonite or may have another composition (polymers) . This mixture has some special properties. The flow behavior of the fluid is an important characteristic for the development of drilling fluid pressure during the different drilling stages. Various types of drilling fluids exist. Generally, the flow behavior of drilling fluid can be described with the Bingham model. The Bingham model describes the fluid by means of a viscosity term and a threshold term from which flow is initialized. The threshold is called the yield point.

D-GEO PIPELINE calculates the required minimum fluid pressure at predefined locations. In these calculations, the flow properties of the drilling fluid (density, viscosity and yield point) play an important role.

During all stages of the drilling process, a pipe is present in the borehole, drill pipe or product pipe. The return flow of drilling fluid with cuttings occurs in the annulus between the borehole wall and the pipe. The required fluid pressure to initiate flow depends on the width of the annulus (radius borehole minus radius drill pipe), the properties of the drilling fluid and the required annular fluid flow rate.

To obtain the minimum required pressure $p_{\text{mud;min}}$, the following pressure values must be calculated and added up:

$$p_{\text{mud;min}} = p_1 + p_2 \tag{24.1}$$

where:

p_1	is the static pressure of the drilling fluid column, in kN/m^2.
p_2	is the excess pressure necessary to maintain the annular flow of drilling fluid with cuttings in the borehole, in kN/m^2.

24.1.1 Static pressure of the drilling fluid column p_1

As the drilling head is at a lower level than the exit point of the drilling fluid, a pressure difference has to be overcome which is equal to the difference in height times the unit weight of the drilling fluid:

$$p_1 = \gamma_{\text{df}} \times (Z_{\text{exit}} - Z) \tag{24.2}$$

where:

γ_{df}	is the unit weight of the drilling fluid, in kN/m^3;

Z_{exit} is the vertical co-ordinate of the exit point of the drilling fluid, in m, depending on the direction of the drilling:
- If the drilling is from left to right, then the exit point of the drilling fluid is the left point: $Z_{\text{exit}} = Z_{\text{left}}$;
- If the drilling is from right to left, then the exit point of the drilling fluid is the right point: $Z_{\text{exit}} = Z_{\text{right}}$

Refer to section 4.6.1.1 for the definitions of Z_{left} and Z_{right}.

Z is the vertical co-ordinate at pipe center, in m.

24.1.2 Excess pressure to maintain flow of drilling fluid p_2

To initiate the flow of drilling fluid, a specific shear resistance in the fluid must be overcome. The drilling fluid flows through an annulus. The required excess fluid pressure depends on the width of the annulus (difference between borehole and drill pipe or product pipe radius), the flow properties of the drilling fluid, and the required flow rate.

The required excess pressure necessary to maintain the annular flow of drilling fluid with cuttings in the borehole p_2 is obtained by multiplying the pressure per unit length with the length of the borehole in which the drilling fluid is flowing:

$$p_2 = \frac{dp}{dz} \times L \tag{24.3}$$

where:

dp/dz is the flow resistance per unit length of borehole, in kN/m^3;
L is the distance in the borehole between the boring front and the exit point of the drilling fluid, in m.

Flow resistance dp/dz

The minimum required pressure dp/dz is the optimal value for which the calculated flow rate Q is equal to the requested flow rate Q_{req} (necessary to initiate flow of drilling fluid).

Calculated flow rate Q

The calculated flow rate Q is the contribution of five components:

$$Q = Q_{1,1} + Q_{1,2} + Q_2 + Q_{3,1} + Q_{3,2} \tag{24.4}$$

with:

$$Q_{1,1} = -2\pi \left[-\frac{\tau_{\text{df}} R_0^3}{3\mu_{\text{df}}} - \frac{dp}{dz}\frac{R_1^2}{4\mu_{\text{df}}} \left(\left(\frac{R_0^4}{4R_1^2} \right) - \lambda^2 \left(R_0^2 \ln\left(\frac{R_0}{R_1}\right) - \frac{1}{2}R_0^2 \right) + \frac{1}{2}C_2 R_0^2 \right) \right] \tag{24.5}$$

$$Q_{1,2} = 2\pi \left[-\frac{\tau_{\text{df}} r_0^3}{3\mu_{\text{df}}} - \frac{dp}{dz}\frac{R_1^2}{4\mu_{\text{df}}} \left(\left(\frac{r_0^4}{4R_1^2} \right) - \lambda^2 \left(r_0^2 \ln\left(\frac{r_0}{R_1}\right) - \frac{1}{2}r_0^2 \right) + \frac{1}{2}C_2 r_0^2 \right) \right] \tag{24.6}$$

$$Q_2 = \pi \left(r_1^2 - r_0^2\right) \left[-\frac{\tau_{\text{df}}}{\mu_{\text{df}}} r_0 - \frac{dp}{dz}\frac{R_1^2}{4\mu_{\text{df}}} \left(\left(\frac{r_0}{R_1} \right)^2 - 2\lambda^2 \ln\left(\frac{r_0}{R_1}\right) + C_2 \right) \right] \tag{24.7}$$

$$Q_{3,1} = -2\pi \left[\frac{\tau_{\text{df}}}{3\mu_{\text{df}}} r_1^3 - \frac{dp}{dz}\frac{R_1^2}{4\mu_{\text{df}}} \left(\left(\frac{r_1^4}{4R_1^2} \right) - \lambda^2 \left(r_1^2 \ln\left(\frac{r_1}{R_1}\right) - \frac{1}{2}r_1^2 \right) + \frac{1}{2}C_4 r_1^2 \right) \right] \tag{24.8}$$

$$Q_{3,2} = 2\pi \left[\frac{\tau_{\text{df}}}{3\mu_{\text{df}}} R_1^3 - \frac{dp}{dz}\frac{R_1^4}{8\mu_{\text{df}}} \left(\frac{1}{2} + \lambda^2 + C_4 \right) \right] \tag{24.9}$$

where:

τ_{df} is the yield point of the drilling fluid, as defined in the *Drilling Fluid Data* window (section 4.6.4), in kN/m^2;
μ_{df} is the plastic viscosity of the drilling fluid, as defined in the *Drilling Fluid Data* window (section 4.6.4), in kN.s/m^2.

The constants are:

$$\lambda^2 = \frac{2\tau_{\text{df}} \times r_0}{R_1^2 \times \frac{dp}{dz}} + \left(\frac{r_0}{R_1}\right)^2 \tag{24.10}$$

$$C_2 = \frac{4\tau_{\text{df}}}{R_1^2 \times \frac{dp}{dz}} \times \left[r_0 \times \ln\left(\frac{R_0}{R_1}\right) - R_0\right] - \left(\frac{R_0}{R_1}\right)^2 + 2\left(\frac{r_0}{R_1}\right)^2 \times \ln\left(\frac{R_0}{R_1}\right) \tag{24.11}$$

$$C_4 = \frac{4\tau_{\text{df}}}{R_1 \times \frac{dp}{dz}} - 1 \tag{24.12}$$

$$r_1 = \frac{2\tau_{\text{df}}}{\frac{dp}{dz}} + r_0 \tag{24.13}$$

r_0 is the solution to the following equation:

$$\frac{\tau_{\text{df}}^2}{\frac{dp}{dz}} + \tau_{\text{df}} r_0 \left[1 + \ln\left(\left(\frac{2\tau_{\text{df}}}{\frac{dp}{dz}} + r_0\right)\frac{R_0}{r_0 R_1}\right)\right] - \tau_{\text{df}}\left(R_0 + R_1\right) + \frac{1}{4}\frac{dp}{dz}\left(R_1^2 - R_0^2\right) + \frac{1}{2}\frac{dp}{dz} r_0^2 \ln\left[\left(\frac{2\tau_{\text{df}}}{\frac{dp}{dz}} + r_0\right)\frac{R_0}{r_0 R_1}\right] = 0 \tag{24.14}$$

Requested flow rate Q_{req}

The requested flow rate Q_{req} is equal to:

$$Q_{\text{req}} = Q_{\text{ann}} \times (1 - f_{\text{loss}}) \tag{24.15}$$

where:

f_{loss} is the circulation loss factor;
Q_{ann} is the annular back flow rate, in kN/m^3.

24.1.3 Minimum drilling fluid pressure for Stage 1 (pilot pipe in the pilot hole)

For the first drilling stage of the horizontal directional drilling process, the minimum drilling fluid pressure is calculated for the drilling direction from the left and the right, using the following formulas:

$$p_{\text{min,left}}^{\text{pilot}} = p_1 + L_{\text{left}} \times \left(\frac{dp}{dz}\right)_{\text{pilot}} \tag{24.16}$$

$$p_{\text{min,right}}^{\text{pilot}} = p_1 + (L - L_{\text{left}}) \times \left(\frac{dp}{dz}\right)_{\text{pilot}} \tag{24.17}$$

where:

L_{left} is the distance in the borehole between the drilling head and the left exit point of the drilling fluid, in m;

L is the total length of the borehole, in m.

24.1.4 Minimum drilling fluid pressure for Stage 2 (drill pipe in the pre-ream hole)

$$p_{\text{min,left}}^{\text{pre-ream}} = \min\left[P_{\text{min,right}}^{\text{pilot}}; p_1 + L_{\text{left}} \times \left(\frac{dp}{dz}\right)_{\text{pre-ream}}\right] \tag{24.18}$$

$$p_{\text{min,right}}^{\text{pre-ream}} = \min\left[P_{\text{min,left}}^{\text{pilot}}; p_1 + (L - L_{\text{left}}) \times \left(\frac{dp}{dz}\right)_{\text{pre-ream}}\right] \tag{24.19}$$

24.1.5 Minimum drilling fluid pressure for Stage 3 (product pipe in the borehole)

$$p_{\text{min,left}}^{\text{pull}} = \min\left[P_{\text{min,right}}^{\text{pre-ream}}; p_1 + L_{\text{left}} \times \left(\frac{dp}{dz}\right)_{\text{pull}}\right] \tag{24.20}$$

$$p_{\text{min,right}}^{\text{pull}} = \min\left[P_{\text{min,left}}^{\text{pre-ream}}; p_1 + (L - L_{\text{left}}) \times \left(\frac{dp}{dz}\right)_{\text{pull}}\right] \tag{24.21}$$

24.2 Maximum allowable drilling fluid pressure

In the borehole, an excess drilling fluid pressure is maintained to enable sufficient outflow of drilling fluid and cuttings. At high pressures, the borehole will fail through uncontrolled expansion. The cavity expansion theory describes the definition of the maximum allowable drilling fluid pressure at which the wall of the borehole becomes unstable. Such limit pressure is the highest pressure that can be sustained by a cavity in the soil. Logically, this forms an upper boundary for the drilling fluid pressure in the borehole.

When the borehole is created, the drilling fluid will exert pressure on the soil. When the pressure rises above a certain value, plastic deformation of the soil will occur, initially adjacent to the borehole. When the pressure is increased further beyond this value, the zone with plastic deformation will increase. If the zone with plastic deformation reaches the surface a blow-out will occur.

In granular materials (drained soil layers), the drilling fluid pressure may lead to development of cracks around the borehole when the pressure exceeds a certain maximal value which is related to the strain of the borehole wall.

In order to prevent blow-outs or damage to structures close to the borehole, care should be taken that the plastic zone remains within a safe radius around the hole. Therefore the pressure that creates a plastic zone that does not extend beyond the established safe radius must be determined.

To determine the maximum allowable drilling fluid pressure, different formulas are used, depending on the soil material sequence above the pipeline.

24.2.1 Maximum allowable drilling fluid pressure in undrained layers

In undrained layers, the maximum allowable drilling fluid pressure $p_{\text{max;und}}$ is:

$$p_{\text{max;und}} = \sigma'_0 + C_{\text{u;f}} \left[1 - \ln \left(\frac{C_{\text{u;f}}}{G_{\text{f}}} + \left(\frac{R_0}{R_{\text{p;max}}} \right)^2 \right) \right] + u \leq 0.9 \, p_{\text{lim;und}} \tag{24.22}$$

with:

$$p_{\text{lim;und}} = \sigma'_0 + C_{\text{u;f}} \left[1 - \ln \left(\frac{C_{\text{u;f}}}{G_{\text{f}}} \right) \right] + u \tag{24.23}$$

$$\sigma'_0 = \frac{3}{4} \frac{\sigma'_{\text{v}}}{f_\gamma} \tag{24.24}$$

where:

$p_{\text{lim;und}}$	is the limit drilling fluid pressure, in kN/m^2;
$C_{\text{u,f}}$	is the average factorized undrained cohesion, in kN/m^2: $C_{u;f} = C_u / f_{\text{c}}$;
f_{c}	is the partial safety factor on the cohesion.The default value is set to 1.4;
c_{u}	is the average undrained cohesion, in kN/m^2;
σ_0'	is the initial effective stress, in kN/m^2;
σ_{v}'	is the vertical effective stress at the pipe center, in kN/m^2;
f_γ	Partial safety factor on the unit weight.
G_{f}	is the average factorized shear modulus, in kN/m^2: $G_{\text{f}} = \frac{E}{f_{\text{E}} \times 2\,(1+\nu)}$;
f_{E}	is the partial safety factor on Young modulus;
R_{b}	is the radius of the hole, in m;
$R_{\text{p,max}}$	is the maximum allowable radius of the plastic zone, in m: $R_{\text{p;max}} = 0.5\,H$. The default ratio between $R_{\text{p;max}}$ and the soil cover H (default 0.5) can be defined by the user in the *Factors* window (section 4.7.1.1) under the field *Safety factor cover (Undrained layer)*;
H	is the vertical distance between the ground level and the pipe center, in m;
u	is the pore pressure at pipe center, in kN/m^2, see Equation 29.4.

Note: Parameters $C_{u;f}$ and G_{f} are determined using the distance depth average between the ground level and the pipe centre. For example, the weight average undrained cohesion in the configuration in Figure 24.1 is:

$$c_{\text{u}} = \frac{C_{\text{u,2}} \times \left(\frac{1}{h_1} - \frac{1}{h_1+h_2} \right) + C_{\text{u,1}} \times \left(\frac{1}{0.5 D_{\text{o}}} - \frac{1}{h_1} \right)}{\frac{1}{0.5 D_{\text{o}}} - \frac{1}{h_1+h_2}} \tag{24.25}$$

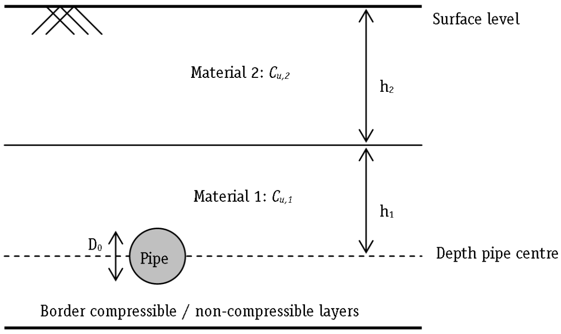


Figure 24.1: *Schematization of h1 and h2*

In case no data about the undrained strength of the soil is available, an estimated c_u value can be obtained using the subsequent formula:

$$c_\text{u} = c \times \cos\varphi + p \times \sin\varphi \tag{24.26}$$

with:

$$p = \frac{\sigma'_\text{v} + \sigma'_\text{h}}{2} \tag{24.27}$$

24.2.2 Maximum allowable drilling fluid pressure in drained layers

According to article E.2.2 of NEN 3650-1 (NEN, 2012a), the maximum allowable drilling fluid pressure in non-compressible drained layers $p_\text{max;d}$ is:

$$p_\text{max;d} = (p'_\text{f} + c_\text{f} \times \cot\varphi_\text{f}) \left[\left(\frac{R_\text{b}}{R_\text{p;max}} \right)^2 + Q \right]^{\frac{-\sin\varphi_\text{f}}{1+\sin\varphi_\text{f}}} - c_\text{f} \times \cot\varphi_\text{f} + u \leq 0.9\, p_\text{lim;d} \tag{24.28}$$

with:

$$p_\text{lim;d} = (p'_\text{f} + c_\text{f} \times \cot\varphi_\text{f}) \times Q^{\frac{-\sin\varphi_\text{f}}{1+\sin\varphi_\text{f}}} - c_\text{f} \times \cot\varphi_\text{f} + u \tag{24.29}$$

$$p'_\text{f} = \sigma'_0 \times (1 + \sin\varphi_\text{f}) + c_\text{f} \times \cos\varphi_\text{f} \tag{24.30}$$

where:

$p_\text{lim;d}$	is the limit drilling fluid pressure, in kN/m^2;
p'_f	is the effective drilling fluid pressure at which the first plastic deformation appears, in kN/m^2;
σ_0'	is the initial effective stress of the soil, in kN/m^2: $\sigma'_0 = \frac{3}{4}\sigma'_\text{v}/f_\gamma$;
φ_f	is the factorized friction angle, in °: $\varphi_\text{f} = \arctan(\tan\varphi/f_\varphi)$;
c_f	is the average factorized cohesion, in kN/m^2: $c_\text{f} = c/f_\text{c}$;
R_b	is the radius of the borehole, in m;
Q	is $(\sigma'_0 \times \sin\varphi_\text{f} + c_\text{f} \times \cos\varphi_\text{f})/G$;
G_f	is the average factorized shear modulus between the border of compressible/non-compressible layers and the pipe center, in kN/m^2: $G_\text{f} = \frac{E}{f_\text{E} \times 2(1+\nu)}$;

$R_{\text{p;max}}$ is the maximum allowable radius of the plastic zone, in m. The plastic zone can be related:
- ◇ either to the soil cover: $R_{\text{p;max}} = 0.5\,H$
- ◇ or to the deformation of the bore hole: $R_{\text{p;max}} = \sqrt{\frac{R_{\text{b}}^2}{Q} \times 2\,\varepsilon_{\text{g;max}}}$

The calculation of the maximum drilling fluid pressure is performed using values determined by both methods for the calculation of the maximum allowable radius of the plastic deformation zone $R_{\text{p;max}}$, after which the minimum value for the maximum allowable drilling fluid pressure is taken.

u is the pore pressure at pipe center, in kN/m^2;

H is the distance between the border of compressible/non-compressible layers and the pipe center, in m;

$\varepsilon_{\text{g;max}}$ is the maximum deformation of the borehole. For sand, $\varepsilon_{\text{g;max}}$ = 0.05.

For the definition of the other symbols, refer to section 25.5.2.

Parameters c, φ and G are determined using two methods:

- ◇ Linear weighted average between the ground level and the pipe center;
- ◇ Distance depth average between the ground level and the pipe center.

24.3 Equivalent diameter for a bundled pipeline

In case of a bundled pipeline, the following equivalent diameter is used for the calculation of the drilling fluid pressures during the pull back operation:

$$D_{\text{eq}} = \sqrt{\sum_{i=1}^{n} D_{\text{o;i}}^2} \tag{24.31}$$

Note: This equivalent diameter is calculated by D-GEO PIPELINE in the *Drilling Fluid Data* window of the *Pipe* menu.

24.4 Equilibrium between drilling fluid pressure and pore pressure

The ratio between the static pressure of the drilling fluid column p_1 and the pore pressure u yields the safety factor, which should be higher than the (user-defined) requested safety factor, which writes:

$$f = \frac{p_1}{u} \geq f_{\text{press;bore}} \tag{24.32}$$

where:

p_1 is the static pressure of the drilling fluid column (i.e. pressure due to the difference of level between the drilling head and the exit point of the drilling fluid), in kN/m^2, see Equation 24.2 in section 24.1.1:
$p_1 = \gamma_{\text{df}} \times (Z_{\text{exit}} - Z)$;

u is the calculated pore pressure (see Equation 29.4 in section 29.5);

$f_{\text{press;bore}}$ is the required safety factor, as defined in the *Factors* window under the field *Contingency factor – Pressure borehole*, see section 4.7.1.1.

25 Strength pipeline calculation

25.1 Buoyancy control

The friction between soil and pipe is partially caused by buoyancy of the pipeline in the drilling fluid. Uplift forces resulting from buoyancy can be neutralized by filling the pipeline. The optimal volume of water (P_{w}) placed in the pipe provides the most advantageous distribution of buoyant forces, as illustrated in Figure 25.1.

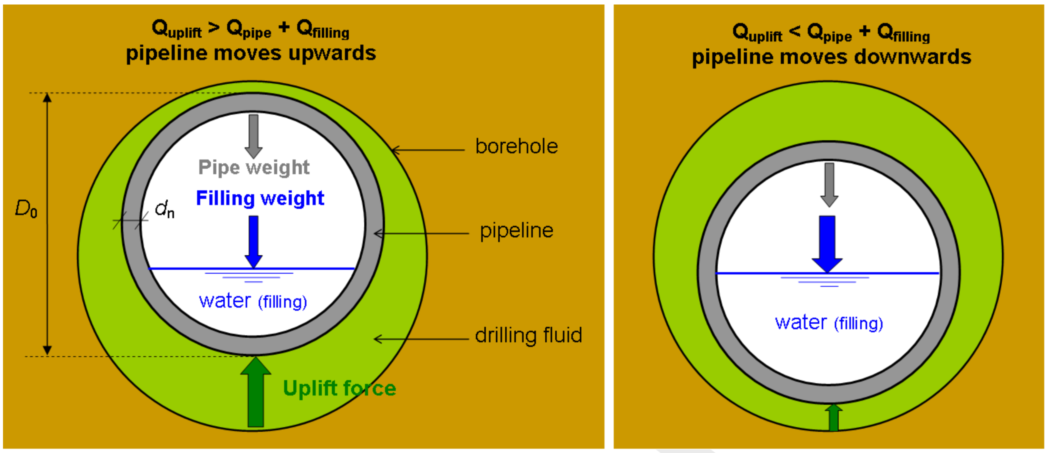


Figure 25.1: *Schematization of the buoyancy control*

The forces acting on the pipeline are:

a) **Uplift force**:

$$Q_{\text{uplift}} = \frac{\pi}{4} \times D_{\text{o}}^2 \times \gamma_{\text{df}} \tag{25.1}$$

b) **Weight of the pipeline**:

$$Q_{\text{pipe}} = \frac{\pi}{4} \times \left(D_{\text{o}}^2 - D_{\text{i}}^2\right) \times \gamma_{\text{b}} \tag{25.2}$$

c) **Weight of the filling (water)**:

$$Q_{\text{filling}} = \frac{\pi}{4} \times D_{\text{i}}^2 \times \gamma_{\text{w}} \times P_{\text{w}} \tag{25.3}$$

The weight of the pipeline filled with water is therefore:

$$Q = Q_{\text{pipe}} + Q_{\text{filling}} \tag{25.4}$$

and the effective weight of the pipeline is defined as:

$$Q_{\text{eff}} = |Q - Q_{\text{uplift}}| \tag{25.5}$$

25.2 Pulling force in a flexible pipeline

According to article E.1.2.1 of NEN 3650-1 (NEN, 2012a), the total pulling force is the contribution of five components:

$$T = T_1 + T_2 + T_{3a} + T_{3b} + T_{3c} \tag{25.6}$$

25.2.1 Roller-lane

According to article E.1.2.2 of NEN 3650-1 (NEN, 2012a), the design pulling force due to friction of the pipeline on the roller-lane T_1 is:

$$T_1 = f_{install} \times L_{rol} \times Q \times f_1 \tag{25.7}$$

where:

$f_{install}$ is the total factor for stochastic variation and model uncertainty, called *Load factor installation* in the *Factors* window (section 4.7.1.1). The default value is set to 1.1;
L_{rol} is the length of the pipeline on the roller-lane, in mm;
Q is the weight of the pipeline filled with water, in N/mm, see Equation 25.4;
f_1 is the factor of friction of the roller-lane, defined in the *Engineering Data* window, see section 4.6.3.1. The default value is set to 0.1.

25.2.2 Straight part of the borehole

According to article E.1.2.3 of NEN 3650-1 (NEN, 2012a), the pulling force in the straight part of the borehole due to friction between pipe and drilling fluid is:

$$T_2 = f_{install} \times L_2 \times (\pi\ D_o \times f_2 + Q_{eff} \times f_3) \tag{25.8}$$

where:

$f_{install}$ is the total factor for stochastic variation and model uncertainty, called *Load factor installation* in the *Factors* window (section 4.7.1.1). The default value is set to 1.1;
L_2 is the length of the pipeline in the straight part of the borehole, in mm;
f_2 is the friction between the pipeline and the drilling fluid, in N/mm^2, defined in the *Engineering Data* window, see section 4.6.3.1. The default value is set to 0.00005 N/mm^2;
Q_{eff} is the effective weight of the pipeline, in N/mm, see Equation 25.5;
f_3 is the factor of friction between the pipeline and the borehole wall, defined in the *Engineering Data* window, see section 4.6.3.1. The default value is set to 0.2.

25.2.3 Curved part of the borehole

According to article E.1.2.4.1 of NEN 3650-1 (NEN, 2012a), the pulling force in the curved part of the borehole due to friction between pipe and drilling fluid T_{3a} is:

$$T_{3a} = f_{install} \times L_b \times (\pi\ D_o \times f_2 + Q_{eff} \times f_3) \tag{25.9}$$

where:

L_b is the length of the pipeline in the curved part of the borehole, in mm.
For the definition of the other symbols, refer to section 25.5.2.

25.2.4 Friction due to soil reaction in the curved part

According to article E.1.2.4.2 of NEN 3650-1 (NEN, 2012a), the pulling force in the curved part of the borehole due to soil reaction T_{3b} is:

$$T_{\text{3b}} = f_{\text{install}} \times 4 \times \frac{q_{\text{r}}}{2} \times D_{\text{o}} \times \frac{\pi}{\lambda} \times f_3 \tag{25.10}$$

with:

$$q_{\text{r}} = k_{\text{v}} \times y \tag{25.11}$$

$$y = \frac{0.3224 \times \lambda^2 \times E_{\text{b}} \times I_{\text{b}}}{D_{\text{o}} \times R} \tag{25.12}$$

$$\lambda = \sqrt[4]{f_{\text{kv}} \times k_{\text{v}} \times \frac{D_{\text{o}}}{4E_{\text{b}}I_{\text{b}}}} \tag{25.13}$$

where:

- q_r is the maximum soil reaction, in N/mm^2;
- k_{v} is the vertical modulus of subgrade reaction, in N/mm^3;
- y is the maximum displacement, in mm;
- λ is the characteristic stiffness pipeline-soil, in mm^{-1};
- f_{kv} is the contingency factor on the modulus of subgrade reaction. The default value is 1.6;
- E_{b} is the Young's modulus of the pipe, in N/mm^2;
- I_{b} is the moment of inertia of the pipe, in mm^4;
- R is the bending radius, in mm;
- f_3 is the factor of friction between the pipeline and the borehole wall, defined in the *Engineering Data* window, see section 4.6.3.1. The default value is set to 0.2.

25.2.5 Friction due to curved forces

According to article E.1.2.4.3 of NEN 3650-1 (NEN, 2012a), the pulling force in the curved part of the borehole due to curved forces T_{3c} is:

$$T_{\text{3c}} = f_{\text{install}} \times L_{\text{b}} \times g_{\text{t}} \times f_3 \tag{25.14}$$

where:

- L_{b} is the length of the curve, in mm: $L_{\text{b}} = 2 \times R \times 2\pi \times \alpha/360$;
- α is the half angle of the curved part, in degrees;
- g_{t} is the curved force, in N/mm: $g_{\text{t}} = (2\,T\,\sin\alpha)\,/L_{\text{b}}$;
- T is the total pulling force in the pipeline, in N, see Equation 25.6.

25.3 Maximum representative pulling force

The maximum representative pulling force $T_{\text{max;rep}}$ in a single pipeline is:

◇ For steel pipe:

$$P_{\text{max;rep}} = A \times \left[\frac{1}{2}\left(-\sigma_{\text{qr}} + \sqrt{\sigma_{\text{qr}}^2 - 4\left(-2.25\,R_{\text{eb}}^2 + \sigma_{\text{qr}}^2\right)}\right) - \sigma_{\text{b}}\right] \tag{25.15}$$

◇ For polyethylene pipe:

$$P_{\text{max;rep}} = A \times (R_{\text{eb;short}} - \alpha \times \sigma_{\text{b}}) \tag{25.16}$$

where:

A	is the cross-section of the pipe, in mm^2: $A = \pi \times (r_0^2 - r_{\text{i}}^2)$;
R_{eb}	is the allowable strength for steel, in N/mm^2, as defined in the *Product Pipe Material Data* window (see section 4.6.2.1);
$R_{\text{eb;short}}$	is the allowable strength at short term for PE, in N/mm^2, as defined in the *Product Pipe Material Data* window (see section 4.6.2.1);
α	is the tensile factor, as defined in the *Product Pipe Material Data* window (see section 4.6.2.1);
δ_{t}	is the negative wall thickness tolerance, in %, as defined in the *Product Pipe Material Data* window (see section 4.6.2.1);
σ_{qr}	is the maximum tangential stress in LC 1B, in N/mm^2, see Equation 25.31;
σ_{b}	is the axial stress in LC 1B, in N/mm^2, see Equation 25.27.

25.4 Pulling force for a bundled pipeline

Important parameters for the pullback operation are the total weight of the (filled/ not filled) pipelines with respect to drilling fluid, which determines the soil reaction force on the bore hole wall in straight sections of the drilling line and the total stiffness of the bundled pipeline, which determines the soil reaction force in curved sections of the drilling line. The pulling force is calculated for an equivalent pipeline with the parameters of the bundle.

$$EI_{\text{eq}} = \sum_{i=1}^{n} EI_{\text{i}} \tag{25.17}$$

$$G_{\text{tot}} = \sum_{i=1}^{n} \left(\frac{1}{4}\pi D_{0;i}^2 - \frac{1}{4}\pi \left(D_{0;i} - 2d_{\text{n;i}}\right)^2 \right) \times \gamma_{\text{i}} \tag{25.18}$$

$$D_{\text{eq}} = f \times \sum_{i=1}^{n} D_{\text{o;i}} \tag{25.19}$$

The equivalent diameter can be used to determine the equivalent wall thickness of the pipeline:

$$\frac{G_{\text{tot}}}{\gamma_{\text{eq}}} = \frac{1}{4}\pi \left(D_{\text{eq}}^2 - \left(D_{\text{eq}} - 2d_{\text{n;eq}}\right)^2\right) \tag{25.20}$$

$$d_{\text{n;eq}} = \frac{D_{\text{eq}} - \sqrt{D_{\text{eq}}^2 - \sum_{i=1}^{n} D_{0;i}^2 - \left(D_{\text{o;i}} - 2d_{\text{n;i}}\right)^2}}{2} \tag{25.21}$$

where:

n	is the number of pipelines in bundle;

$D_{\text{o;i}}$ is the outer diameter of pipeline number i, in m;
D_{eq} is the equivalent diameter of the pipeline, in m;
$d_{\text{n;i}}$ is the wall thickness of pipeline number i, in m;
$d_{\text{n;eq}}$ is the equivalent wall thickness of the pipeline, in m;
γ_{i} is the unit weight of the material of pipeline number i, in kN/m^3;
γ_{eq} is the equivalent unit weight of the pipeline material, in kN/m^3;
f is a factor: $f = 1/n^{0.3}$.

The calculated pulling force is acting on all the pipelines in the bundle. The magnitude of the pulling force of a single pipeline can be determined as follows:

$$T_{\text{i}} = \frac{\left(\frac{\pi}{4}\, D_{\text{o;i}}^2 - \frac{\pi}{4}\, \left(D_{\text{o;i}} - 2\, d_{\text{n;i}}\right)^2\right)}{\sum\limits_{i=1}^{n} \left(\frac{\pi}{4}\, D_{\text{o;i}}^2 - \frac{\pi}{4}\, \left(D_{\text{o;i}} - 2\, d_{\text{n;i}}\right)^2\right)} \times T_{\text{total}} \tag{25.22}$$

In case the stiffness of the pipeline materials is significantly different (for example a combined bundle of steel and PE pipelines), a different approach is applied. In addition to the previous align, the total pulling force is divided over the stiff steel pipelines. The PE pipelines are then considered as single pulled in pipelines.

25.5 Strength calculation

In order to consider the strength of the pipeline, calculations for five load combinations are carried out according to NEN 3650:

- Load combination 1A: start of the pullback operation (section 25.5.1)
- Load combination 1B: end of the pullback operation (section 25.5.2)
- Load combination 2: application of internal pressure (section 25.5.3)
- Load combination 3: pipeline in operation, without internal pressure (section 25.5.4)
- Load combination 4 : pipeline in operation, with internal pressure (section 25.5.5)

25.5.1 Strength calculation for Load Combination 1A: start of the pullback operation

Axial stress:

At start of the pull back operation, the axial bending stress σ_{b} is:

$$\sigma_{\text{b}} = \frac{M_{\text{b}}}{W_{\text{b}}} = \frac{f_{\text{k}} \times E_{\text{b}} \times I_{\text{b}}}{R_{\text{rol}} \times W_{\text{b}}} \tag{25.23}$$

Note: f_{k} is the overall safety factor on moment, as prescribed in article E.1.3 of NEN 3650-1. In D-GEO PIPELINE, this overall factor is indeed the contribution of three safety factors:

$$f_{\text{k}} = \frac{f_{\text{M}} \times f_{\text{install}}}{f_{\text{R}}} \tag{25.24}$$

where:

f_{M} is the contingency factor on moment: 1.27 for steel pipe and 1.4 for PE pipe;
f_{R} is the contingency factor on bending radius: 1.1 for steel pipe and 1 for PE pipe;
f_{install} is the load factor on installation: 1.1 for steel pipe and 1 for PE pipe.

The axial stress due to pull-back is:

$$\sigma_{\mathrm{t}} = f_{\mathrm{pull}} \times \frac{T_1}{A} \tag{25.25}$$

where:

T_1 is the design pulling force due to friction of the pipeline on the roller-lane, see Equation 25.7.

For the definition of the other symbols, refer to section 25.5.2.

The maximum axial stress is:

$$\sigma_{\mathrm{a;max}} = \max\left(\left|\sigma_{\mathrm{t}} + \alpha \times \sigma_{\mathrm{b}}\right|; \left|\sigma_{\mathrm{t}} - \alpha \times \sigma_{\mathrm{b}}\right|\right) \tag{25.26}$$

Tangential stress:

At start of the pull back operation, the pipeline is situated on the rollers, the tangential stress is negligible.

25.5.2 Strength calculation for Load Combination 1B: end of the pullback operation

Axial stresses:

At the end of the pull back operation, the axial bending stress:

$$\sigma_{\mathrm{b}} = \frac{M_{\mathrm{b}}}{W_{\mathrm{b}}} = \frac{f_{\mathrm{k}} \times E_{\mathrm{b}} \times I_{\mathrm{b}}}{R_{\mathrm{min}} \times W_{\mathrm{b}}} \tag{25.27}$$

The axial stress due to pull-back is:

$$\sigma_{\mathrm{t}} = f_{\mathrm{pull}} \times \frac{T_{\mathrm{max}}}{A} \tag{25.28}$$

The maximum axial stress is:

$$\sigma_{\mathrm{a;max}} = \max\left(\left|\sigma_{\mathrm{t}} + \alpha \times \sigma_{\mathrm{b}}\right|; \left|\sigma_{\mathrm{t}} - \alpha \times \sigma_{\mathrm{b}}\right|\right) \tag{25.29}$$

where:

R_{min} is the minimum bending radius of the pipeline configuration (i.e. minimum between R_{left}, R_{right} and the horizontal bending radius), in m. In case of a combined 3-dimensional bending radius, see Equation 22.5.

T_{max} is the maximum pulling force, in kN (see section 25.2).

Note: f_{k} is the overall safety factor on moment, as prescribed in article E.1.3 of NEN 3650-1. In D-GEO PIPELINE, this overall factor is indeed the contribution of three safety factors:

$$f_{\mathrm{k}} = \frac{f_{\mathrm{M}} \times f_{\mathrm{install}}}{f_{\mathrm{R}}} \tag{25.30}$$

Table 25.12: Moment and deflection coefficients for indirectly and directly transmitted stress as a function of the bedding angle β, according to Table D.2 of NEN 3650-1

Load angle	Direct coefficients			Indirect coefficients		
β	K_t	K_b	k_y	K'_t	K'_b	k'_y
0°	0.150	0.294	0.116	0.080	0.239	0.074
30°	0.148	0.235	0.113	0.078	0.179	0.071
60°	0.143	0.189	0.105	0.073	0.134	0.064
70°	0.141	0.178	0.102	0.071	0.122	0.061
90°	0.137	0.157	0.096	0.067	0.102	0.055
120°	0.131	0.138	0.089	0.061	0.083	0.048
150°	0.126	0.128	0.085	0.056	0.073	0.043
180°	0.125	0.125	0.083	0.055	0.070	0.042

Tangential stresses:

The tangential stress (indirectly transmitted) as a result of the bending is:

$$\sigma_{\text{qr}} = \max\left(\sigma_{\text{qr;b}}; \sigma_{\text{qr;t}}\right) \tag{25.31}$$

with:

$$\sigma_{\text{qr;b}} = K'_{\text{b}} \times q_r \times \frac{r_{\text{g}}}{W_{\text{w}}} \times D_{\text{o}} \qquad \text{(at the bottom of the pipe)}$$

$$\sigma_{\text{qr;t}} = K'_{\text{t}} \times q_r \times \frac{r_{\text{g}}}{W_{\text{w}}} \times D_{\text{o}} \qquad \text{(at the top of the pipe)}$$

where:

- q_{r} is the soil reaction, in kN/m^2, see Equation 25.11 with R = the minimum bending radius;
- K_{b}' is the moment coefficient for indirectly transmitted stress at the bottom of the pipeline, depending on the bedding angle β as shown in Table 25.12;
- K_{t}' is the moment coefficient for indirectly transmitted stress at the top of the pipeline, depending on the bedding angle β as shown in Table 25.12;
- W_{w} is the wall resisting moment in m^3/m: $W_{\text{w}} = d_{\text{n}}^2/6.$

For the definition of the other symbols, refer to section 25.5.2.

The maximum tangential stress is:

$$\sigma_{\text{t;max}} = \sigma_{\text{qr}} \tag{25.32}$$

25.5.3 Strength calculation for Load Combination 2: application of internal pressure

According to article 8.5.2.1 of NEN 3651 (NEN, 2012d), the ring stresses around the pipeline σ_{py} and σ_{pt} caused by design (p_{d}) respectively test (p_{t}) internal pressure are:

◇ For piles with a thin wall ($D_{\text{g}}/d < 20$):

$$\sigma_{\text{py}} = f_{\text{pd}} \times p_{\text{d}} \times \frac{D_{\text{g}}}{2 \times d} \tag{25.33}$$

$$\sigma_{\text{pt}} = f_{\text{pt}} \times p_t \times \frac{D_{\text{g}}}{2 \times d} \tag{25.34}$$

◇ For piles with a thick wall ($D_{\text{g}}/d \geq 20$):

$$\sigma_{\text{py}} = f_{\text{pd}} \times p_{\text{d}} \times \frac{r_0^2 + r_{\text{i}}^2}{r_0^2 - r_{\text{i}}^2} \tag{25.35}$$

$$\sigma_{\text{pt}} = f_{\text{pt}} \times p_{\text{t}} \times \frac{r_0^2 + r_{\text{i}}^2}{r_0^2 - r_{\text{i}}^2} \tag{25.36}$$

The axial internal stress σ_{px} is:

$$\sigma_{\text{px}} = \nu \times \sigma_{\text{pt}} = 0.5 \times \sigma_{\text{pt}} \tag{25.37}$$

25.5.4 Strength calculation for Load Combination 3: pipeline in operation, without internal pressure

Axial stresses:

When the pipeline is in operation, the axial bending stress σ_{b} is:

$$\sigma_{\text{b}} = \frac{M_{\text{b}}}{W_{\text{b}}} = \frac{f_{\text{k}} \times E_{\text{b}} \times I_{\text{b}}}{R_{\text{min}} \times W_{\text{b}}} \tag{25.38}$$

The maximum axial stress is:

$$\sigma_{\text{a;max}} = \alpha \times \sigma_{\text{b}} \tag{25.39}$$

Tangential stresses:

The tangential stress (indirectly transmitted) as a result of the bending is:

$$\sigma_{\text{qr}} = \max\left(\sigma_{\text{qr;b}}; \sigma_{\text{qr;t}}\right) \tag{25.40}$$

with:

$$\sigma_{\text{qr;b}} = K'_{\text{b}} \times q_r \times \frac{r_{\text{g}}}{W_{\text{w}}} \times D_{\text{o}} \qquad \text{(at the bottom of the pipe)}$$

$$\sigma_{\text{qr;t}} = K'_{\text{t}} \times q_r \times \frac{r_{\text{g}}}{W_{\text{w}}} \times D_{\text{o}} \qquad \text{(at the top of the pipe)}$$

The tangential stress (directly transmitted) as a result of the bending is:

$$\sigma_{\text{qn}} = \max\left(\sigma_{\text{qn;b}}; \sigma_{\text{qn;t}}\right) \tag{25.41}$$

with:

$$\sigma_{\text{qn;b}} = K_{\text{b}} \times q_{\text{n,r,v}} \times \frac{r_{\text{g}}}{W_{\text{w}}} \times D_{\text{o}} \qquad \text{(at the bottom of the pipe)}$$

$$\sigma_{\text{qn;t}} = K_{\text{t}} \times q_{\text{n,r,v}} \times \frac{r_{\text{g}}}{W_{\text{w}}} \times D_{\text{o}} \qquad \text{(at the top of the pipe)}$$

$$q_{\text{n,r,v}} = f_{\text{Qn1}} \times f_{\text{Qn2}} \times \left(q_{\text{n,r}} + q_{\text{v}}\right)$$

The maximum tangential stress is:

$$\sigma_{\text{t;max}} = \alpha \times \max\left(\left|\sigma_{\text{qr;b}} + \sigma_{\text{qn;b}}\right| ; \left|\sigma_{\text{qr;t}} + \sigma_{\text{qn;t}}\right|\right) \tag{25.42}$$

where:

f_{Qn1}	is the load factor on soil stress q_{n}, as defined in the *Factors* window (see section 4.7.1.1). The default value is set to 1.5 for steel and 1 for polyethylene;
f_{Qn2}	is the contingency factor on soil stress q_{n}, as defined in the *Factors* window (see section 4.7.1.1). The default value is set to 1.1;
K_{b}	is the moment coefficient for directly transmitted stress at the bottom of the pipeline, depending on the bedding angle β as shown in Table 25.12;
K_{t}	is the moment coefficient for directly transmitted stress at the top of the pipeline, depending on the bedding angle β as shown in Table 25.12;
$q_{\text{n,r,v}}$	is the (maximum) reduced vertical stress $q_{\text{n,r}}$ increased with a possible traffic load q_{v}, including safety factors, in kN/m^2;
$q_{\text{n,r}}$	is the neutral reduced soil stress, in kN/m^2, see section 23.3;
q_{v}	is the traffic load, in kN/m^2, see section 23.14;

For the definition of the other symbols, refer to section 25.5.2.

25.5.5 Strength calculation for Load Combination 4: pipeline in operation, with internal pressure

Axial stresses:

The axial bending stress σ_{b} is:

$$\sigma_{\text{b}} = \frac{M_{\text{b}}}{W_{\text{b}}} = \frac{f_{\text{k}} \times E_{\text{b}} \times I_{\text{b}}}{R_{\text{min}} \times W_{\text{b}}} \tag{25.43}$$

The ring stresses around the pipeline caused by design internal pressure and σ_{py} and test internal pressure σ_{pt} are

$$\sigma_{\text{py}} = f_{\text{pd;comb}} \times p_{\text{d}} \times \frac{D_{\text{o}} - d}{2 \times d} \tag{25.44}$$

$$\sigma_{\text{pt}} = f_{\text{pt}} \times p_t \times \frac{D_{\text{o}} - d}{2 \times d} \qquad \text{for steel} \tag{25.45}$$

$$\sigma_{\text{pt}} = f_{\text{pt}} \times p_t \times \frac{r_0^2 + r_{\text{i}}^2}{r_0^2 - r_{\text{i}}^2} \qquad \text{for polyethylene} \tag{25.46}$$

The axial internal stress σ_{px} is:

$$\sigma_{\text{px}} = \nu \times \sigma_{\text{py}} = 0.5\ \sigma_{\text{py}} \tag{25.47}$$

The axial internal stress due to temperature variation σ_{temp} is, according to article D.2.2 of NEN 3650-1:

$$\sigma_{\text{temp}} = \Delta t \times \alpha_{\text{g}} \times E_{\text{b}} \tag{25.48}$$

where:

Δt is the temperature variation in °c, as defined in the *Product Pipe Material Data* window, see section 4.6.2.1;
α_g is the linear settlement coefficient, in (mm/mm)K^{-1}, as defined in the *Engineering Data* window, see section 4.6.3.1;
E_b is the Young's modulus of the pipe (at long term for polyethylene), in kN/m^2.

The maximum axial stress is:

$$\sigma_{a;max} = \alpha \times \sigma_b + \sigma_{px} \tag{25.49}$$

Tangential stresses:

The tangential stress (indirectly transmitted) as a result of the bending is:

$$\sigma_{qr} = \max\left(\sigma_{qr;b}; \sigma_{qr;t}\right) \tag{25.50}$$

with:

$$\sigma_{qr;b} = K'_b \times q_r \times \frac{r_g}{W_w} \times D_o \qquad \text{(at the bottom of the pipe)}$$

$$\sigma_{qr;t} = K'_t \times q_r \times \frac{r_g}{W_w} \times D_o \qquad \text{(at the top of the pipe)}$$

The tangential stress (directly transmitted) as a result of the bending is:

$$\sigma_{qn} = \max\left(\sigma_{qn;b}; \sigma_{qn;t}\right) \tag{25.51}$$

with:

$$\sigma_{qn;b} = K_b \times q_{n,r,v} \times \frac{r_g}{W_w} \times D_o \qquad \text{(at the bottom of the pipe)}$$

$$\sigma_{qn;t} = K_t \times q_{n,r,v} \times \frac{r_g}{W_w} \times D_o \qquad \text{(at the top of the pipe)}$$

$$q_{n,r,v} = f_{Qn1} \times f_{Qn2} \times \left(q_{n,r} + q_v\right)$$

Refer to section 25.5.4 for the definition of the symbols.

The maximum tangential stress is:

$$\sigma_{t;max} = \sigma_{py} + \alpha \times \left(F'_{rr} \times \sigma_{qr} + F_{rr} \times \sigma_{qn}\right) \tag{25.52}$$

with:

$$F_{rr} = \frac{1}{1 + \frac{2p_d \times r_g^3 \times k_y}{E_b \times I_w}} \tag{25.53}$$

$$F'_{rr} = \frac{1}{1 + \frac{2p_d \times r_g^3 \times k'_y}{E_b \times I_w}} \tag{25.54}$$

where:

F_{rr} is the direct re-rounding factor;
F_{rr}' is the indirect re-rounding factor;

I_w is the moment of inertia of the wall, in m^3: $I_w = d_n^3/12$;
k_y is the direct deflection factor depending on the bedding angle β as shown in Table 25.12;
k_y' is the indirect deflection factor depending on the bedding angle β as shown in Table 25.12;
For the definition of the other symbols, refer to section 25.5.2.

25.6 Check of calculated stresses

25.6.1 Check of calculated stresses according to the Dutch standard NEN

25.6.1.1 Check of calculated stresses acc. to the Dutch standard NEN: Steel pipe

According to article D.3.1 of NEN 3650-2 (NEN, 2012b), the calculated stresses (for the load combinations) must meet the following conditions:

◇ **For Load Combinations 1A and 1B:**

$$\sigma_V \leq R_{eb}/\gamma_m \tag{25.55}$$

◇ **For Load Combination 2:**

$$\sigma_{py} \leq R_{eb}/\gamma_m \tag{25.56}$$

$$\sigma_{pt} \leq R_{eb}/\gamma_{m;test} \tag{25.57}$$

$$\sigma_{pm} \leq 1.1\ R_{eb}/\gamma_m \tag{25.58}$$

◇ **For Load Combinations 3 and 4:**

$$\sigma_{V;max} \leq 0.85\ (R_{eb} + R_{e;20^\circ})\,/\gamma_m \tag{25.59}$$

with:

$$\sigma_V = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \times \sigma_y} \tag{25.60}$$

$$\sigma_{V;i} = \sqrt{\sigma_{x;i}^2 + \sigma_{y;i}^2 - \sigma_{x;i} \times \sigma_{y;i}} \tag{25.61}$$

$$\sigma_{pm} = \sqrt{\sigma_{px}^2 + \sigma_{py}^2 - \sigma_{px} \times \sigma_{py}} \tag{25.62}$$

where:

$\sigma_{V;max}$ is the maximum acting stress, in kN/m^2: $\sigma_{V;max} = \max\left(\sigma_{V;1}; \sigma_{V;2}; \sigma_{V;3}; \sigma_{V;4}\right)$;
$\sigma_{V;i}$ is the calculated acting stress, in kN/m^2:
– i=1 ($\sigma_{V;1}$) corresponds to the primary membrane stress
– i=2 ($\sigma_{V;2}$) corresponds to the total primary stress
– i=3 ($\sigma_{V;3}$) corresponds to the total membrane stress
– i=4 ($\sigma_{V;4}$) corresponds to the resultant of primary and secondary stresses.
For the determination of $\sigma_{V;i}$, four combinations of ($\sigma_{x;i}$; $\sigma_{y;i}$) are tested (top and bottom of the pipe combined with inside or outside), and the maximum value is used for the check. Those four combinations are given in Table 25.17 to Table 25.20;
σ_{py} is the tangential stress due to design pressure, in kN/m^2;
σ_{ptest} is the tangential stress due to test pressure, in kN/m^2;
$\sigma_{x;i}$ is the axial stress, in kN/m^2;
$\sigma_{y;i}$ is the tangential stress, in kN/m^2;

γ_{m} is the partial material factor, as defined in the *Product Pipe Material Data* window (see section 4.6.2.1;

$\gamma_{\text{m;test}}$ is the partial material factor for test pressure, as defined in the *Product Pipe Material Data* window (see section 4.6.2.1;

R_{eb} is the yield strength, in kN/m^2, as defined in the *Product Pipe Material Data* window (see section 4.6.2.1);

$R_{\text{e;20}}$ is the yield strength at a temperature of 20°c, in kN/m^2.

Table 25.17: *Set for calculation of the maximum stresses for load combination 1A*

	Top outside	Top inside	Bottom inside	Bottom outside
σ_{x}	$\sigma_{\text{t}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{t}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{t}} + \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{t}} + \alpha \times \sigma_{\text{b}}$
σ_{y}	0	0	0	0

Table 25.18: *Set for calculation of the maximum stresses for load combination 1B*

	Top outside	Top inside	Bottom inside	Bottom outside
σ_{x}	$\sigma_{\text{t}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{t}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{t}} + \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{t}} + \alpha \times \sigma_{\text{b}}$
σ_{y}	$-\sigma_{\text{qr;t}}$	$\sigma_{\text{qr;t}}$	$\sigma_{\text{qr;b}}$	$-\sigma_{\text{qr;b}}$

Table 25.19: *Set for calculation of the maximum stresses for load combination 3*

	Top outside	Top inside	Bottom inside	Bottom outside
$\sigma_{\text{x;2}}$	0	0	0	0
$\sigma_{\text{y;2}}$	$-\sigma_{\text{qr;t}}$	$\sigma_{\text{qr;t}}$	$\sigma_{\text{qr;b}}$	$-\sigma_{\text{qr;b}}$
$\sigma_{\text{x;3}}$	$-\alpha \times \sigma_{\text{b}}$	$-\alpha \times \sigma_{\text{b}}$	$\alpha \times \sigma_{\text{b}}$	$\alpha \times \sigma_{\text{b}}$
$\sigma_{\text{y;3}}$	0	0	0	0
$\sigma_{\text{x;4}}$	$-\alpha \times \sigma_{\text{b}}$	$-\alpha \times \sigma_{\text{b}}$	$\alpha \times \sigma_{\text{b}}$	$\alpha \times \sigma_{\text{b}}$
$\sigma_{\text{y;4}}$	$-\sigma_{\text{qr;t}} - \sigma_{\text{qn;t}}$	$\sigma_{\text{qr;t}} + \sigma_{\text{qn;t}}$	$\sigma_{\text{qr;b}} + \sigma_{\text{qn;b}}$	$-\sigma_{\text{qr;b}} - \sigma_{\text{qn;b}}$

Table 25.20: *Set for calculation of the maximum stresses for load combination 4*

	Top outside	Top inside	Bottom inside	Bottom outside
$\sigma_{\text{x;1}}$	σ_{px}	σ_{px}	σ_{px}	σ_{px}
$\sigma_{\text{y;1}}$	σ_{py}	σ_{py}	σ_{py}	σ_{py}
$\sigma_{\text{x;2}}$	σ_{px}	σ_{px}	σ_{px}	σ_{px}
$\sigma_{\text{y;2}}$	$\sigma_{\text{py}} - F_{\text{rr}} \times \sigma_{\text{qn;t}}$	$\sigma_{\text{py}} + F_{\text{rr}} \times \sigma_{\text{qn;t}}$	$\sigma_{\text{py}} + F_{\text{rr}} \times \sigma_{\text{qn;b}}$	$\sigma_{\text{py}} - F_{\text{rr}} \times \sigma_{\text{qn;b}}$
$\sigma_{\text{x;3}}$	$\sigma_{\text{px}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{px}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{px}} + \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{px}} + \alpha \times \sigma_{\text{b}}$
$\sigma_{\text{y;3}}$	σ_{py}	σ_{py}	σ_{py}	σ_{py}
$\sigma_{\text{x;4}}$	$\sigma_{\text{px}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{px}} - \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{px}} + \alpha \times \sigma_{\text{b}}$	$\sigma_{\text{px}} + \alpha \times \sigma_{\text{b}}$
$\sigma_{\text{y;4}}$	$\sigma_{\text{py}} - \alpha(F_{\text{rr}} \times \sigma_{\text{qn;t}} + F'_{\text{rr}} \times \sigma_{\text{qr;t}})$	$\sigma_{\text{py}} + \alpha(F_{\text{rr}} \times \sigma_{\text{qn;t}} + F'_{\text{rr}} \times \sigma_{\text{qr;t}})$	$\sigma_{\text{py}} + \alpha(F_{\text{rr}} \times \sigma_{\text{qn;b}} + F'_{\text{rr}} \times \sigma_{\text{qr;b}})$	$\sigma_{\text{py}} - \alpha(F_{\text{rr}} \times \sigma_{\text{qn;b}} + F'_{\text{rr}} \times \sigma_{\text{qr;b}})$

Note: α is the tensile factor (only used for polyethylene), as defined in the *Product Pipe Material Data* window (see section 4.6.2.1).

Note: For load combination 4, the acting stresses $\sigma_{\text{V;1}}$ to $\sigma_{\text{V;4}}$ are calculated with a load factor "in combination" ($f_{\text{pd;comb}}$) for the design pressure.

25.6.1.2 Check of calculated stresses acc. to the Dutch standard NEN: Polyethylene pipe

The calculated stresses must meet the following conditions:

$$\sigma \leq S \times R_{\text{eb;short}} \qquad \text{for LC 1 and 2 (test pressure)} \tag{25.63}$$

$$\sigma \leq S \times R_{\text{eb;long}} \qquad \text{for LC 2 (internal pressure), 3 and 4} \tag{25.64}$$

where:

σ is the calculated stress, in kN/m^2;
$R_{\text{eb;short}}$ is the allowable strength at short term, in kN/m^2;
$R_{\text{eb;long}}$ is the allowable strength at long term, in kN/m^2;
S is the factor of importance, as defined in the *Factors* window (see section 4.7.1.1).

25.7 Deflection of the pipe

According to article D.4.2 (case 5 - HDD) of NEN 3650-1 (NEN, 2012a), the deflection of the pipeline is:

$$\delta_{\text{y}} = \frac{D_{\text{o}} \times r_{\text{g}}^3}{E_{\text{b}} \times I_{\text{w}}} \times \left(k_{\text{y}} \times q_{\text{n,r,v}} + 0.083 \times q_{\text{h,r}} + k_{\text{y}}' \times q_{\text{r}}\right) \tag{25.65}$$

where:

$q_{\text{n,r,v}}$ is the corrected neutral reduced vertical stress $q_{\text{n;r}}$ (see section 23.3) increased with a possible traffic load q_{v} (see section 23.14), including safety factors, in kN/m^2: $q_{\text{n,r,v}} = f_{\text{Qn1}} \times f_{\text{Qn2}} \times (q_{\text{n;r}} + q_{\text{v}})$;
$q_{\text{h,r}}$ is the neutral reduced horizontal stress in kN/m^2, see Equation 23.12;
q_{r} is the soil reaction in kN/m^2, see Equation 25.11 with R = the minimum bending radius.
k_{y} is the direct deflection coefficient depending on the bedding angle β, see Table 25.12;
k_{y}' is the indirect deflection coefficient depending on the bedding angle β, see Table 25.12;
f_{Qn1} is the load factor on soil stress q_{n}, as defined in the *Factors* window (see section 4.7.1.1). The default value is set to 1.5 for steel and 1 for polyethylene;
f_{Qn2} is the contingency factor on soil stress q_{n}, as defined in the *Factors* window (see section 4.7.1.1). The default value is set to 1.1;
E_{b} is the Young's modulus of the pipe. For PE, the modulus at long term is used.

25.8 Implosion of the polyethylene pipe

According to article 8.5.5.1 of NEN 3650-3 for polyethylene, the maximum allowable external pressure p_0 is:

$$p_0 = \frac{1}{\gamma_{\text{imp}}\ (1-\nu^2)} \times \frac{24 \times E_{\text{b}} \times I_{\text{w}}}{D_{\text{g}}^3} \tag{25.66}$$

where:

E_{b} is the Young's modulus of the polyethylene pipe, in kN/m^2;
ν is the Poisson ratio of polyethylene: $\nu = 0.4$;
γ_{imp} is the safety factor on implosion, as defined in the *Factors* window (see section 4.7.1.1).
For the definition of the other symbols, refer to section 25.5.2.

The check on implosion is performed during the pull-back operation (section 25.8.1) and at serviceability limit state when the pipe is in operation (section 25.8.2).

25.8.1 Check on implosion during the pull-back operation

During the pull-back operation, the drilling fluid pressure gives an external pressure on the pipe. The highest minimum required drilling fluid pressure should not exceed the maximum allowable external pressure. This writes:

$$\max\left(p_{\text{mud;min}}\right) \leq p_0 \tag{25.67}$$

where γ = 1.5 and E is the module at short term, for the calculation of p_0.

If the pipe is completely filled, the filling fluid gives an internal fluid pressure called filling resistance p_{fill} of:

$$p_{\text{fill}} = \left(\min\left(Z_{\text{left}}; Z_{\text{right}}\right) - Z_{\text{bottom}}\right) \times \gamma_{\text{fill}} \tag{25.68}$$

The maximum allowable external pressure becomes therefore $p_0 + p_{\text{fill}}$ and the check on implosion becomes:

$$\max\left(p_{\text{mud;min}}\right) \leq p_0 + p_{\text{fill}} \tag{25.69}$$

25.8.2 Check on implosion when the pipe is in operation

In operation, the water pressure at the lowest point of the drilling gives an external pressure on the pipe. This maximum pore pressure should not exceed the maximum allowable external pressure. This writes:

$$u_{\text{max}} \leq p_0 \tag{25.70}$$

where γ = 3 and E is the module at long term, for the calculation of p_0.

If the pipe is completely filled, the maximum allowable external pressure becomes $p_0 + p_{\text{fill}}$ and the check on implosion becomes:

$$u_{\text{max}} \leq p_0 + p_{\text{fill}} \tag{25.71}$$

26 Micro tunneling

26.1 Support pressures and thrust forces

Drilling through the soil changes the stress conditions in the soil. The deviations from the original stress conditions are largely determined by the size of the overcut and the face support pressure of the applied shield. Small deviations form the original stress conditions are acceptable as the stability of soil adjacent to the micro tunneling machine is maintained. A relative low support pressure may lead to settlement in front of the tunneling machine which in turn may lead to settlement of the surface or to settlement of soil layers below a construction or pipeline. A relative high support pressure can lead to a blow out of drilling fluid or may lead to heave of the surface.

26.1.1 Target support pressure

In order to minimize the effect on the stress conditions, the drilling should be performed using a target support pressure $\sigma_{\mathrm{T;ac}}$ which is close to the neutral horizontal pressure:

$$\sigma_{\mathrm{T;ac}} = \sigma'_{\mathrm{h,n}} + u \tag{26.1}$$

where:

u	is the pore pressure, in kN/m^2 at the shield center, see Equation 29.4.
$\sigma'_{\mathrm{h,n}}$	is the horizontal effective pressure at the shield center, in kN/m^2: $\sigma'_{\mathrm{h,n}} = \sigma'_{\mathrm{v}} \times (1 - \sin \varphi_{\mathrm{b}})$;
σ'_{v}	is the vertical effective stress at the shield center, in kN/m^2, see Equation 29.5;
φ_{b}	is the average angle of internal friction of the soil over the height of the shield.

26.1.2 Minimal support pressure

Under normal circumstances, a relative low support pressure is usually sufficient for stable conditions of the soil adjacent to the micro tunneling machine. The minimal required support pressure is often a little higher than the water pressure. The relative low required minimal support pressure is determined by the type of soil in front of the tunneling machine.

Minimal support pressure in undrained conditions

In case of micro tunneling in an undrained soil type, according to Broms & Bennermark 1967 (Broms and Bennermark, 1967), the minimal support pressure $\sigma_{\mathrm{min;und}}$ is determined by the undrained strength of the soil:

$$\sigma_{\mathrm{min;und}} = f_{\mathrm{cover}} \times \sigma'_{\mathrm{v}} + f_{\mathrm{u}} \times u - N \times \frac{s_{\mathrm{u}}}{f_{\mathrm{c}}} \geq f_{\mathrm{u}} \times u \tag{26.2}$$

where:

s_{u}	is the average undrained shear strength between the surface and the top of the shield of the micro tunneling machine , in kN/m^2;
f_{c}	is the safety factor on cohesion as defined in the *Factors* window, see section 4.7.1.2 (default is 1.4).
f_{cover}	is the contingency factor on soil cover as defined in the *Factors* window, see section 4.7.1.2 (default is 1.1);
f_{u}	is the safety factor on water pressure as defined in the *Factors* window, see section 4.7.1.2 (default is 1.05);
N	is the face stability ratio as defined in the *Factors* window, see section 4.7.1.2;

σ'_{v} is the vertical effective stress at the shield center, in kN/m^2, see Equation 29.5;
u is the pore pressure, see Equation 29.4.

The required stability index N depends upon the depth/diameter ratio of the tunneling machine. In Figure 26.1 the upper and lower boundaries according to (Davis *et al.*, 1980) are described.

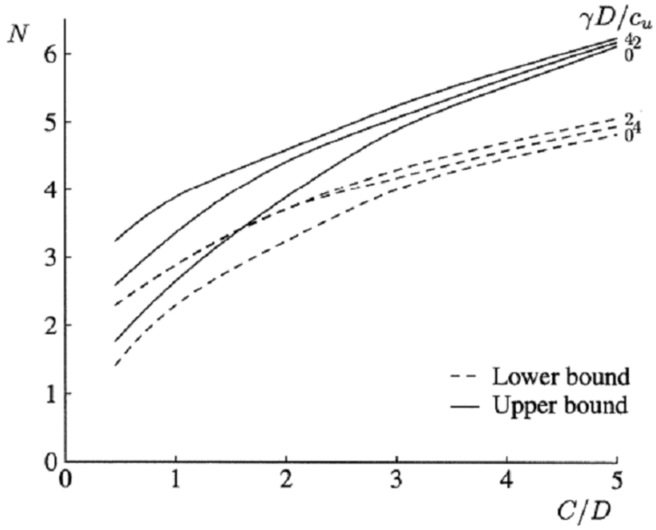


Figure 26.1: *Upper and lower bound for the stability ratio N (Davis et al., 1980)*

Minimal support pressure in drained conditions

In granular soils which behave drained during drilling, the minimal support pressure based on 3 dimensional effects can be calculated using the method which is developed by (Jancesz and Steiner, 1994). The minimal effective stress required for stability of the soil next to the shield is defined as follows:

$$\sigma'_{\text{h}} = f_{\sigma\text{h}} \times K_{\text{A3}} \times \sigma'_{\text{v}} \tag{26.3}$$

The total minimal support pressure is drained layers $\sigma_{\text{min;d}}$ can be calculated as follows:

$$\sigma_{\text{min;d}} = f_{\sigma\text{h}} \times K_{\text{A3}} \times \sigma'_{\text{v}} + f_{\text{u}} \times u \tag{26.4}$$

where:

f_{u} is the safety factor on water pressure as defined in the *Factors* window, see section 4.7.1.2 (default is 1.05);
$f_{\sigma\text{h}}$ is the safety factor on horizontal effective stress as defined in the *Factors* window, see section 4.7.1.2 (default is 1.5);
K_{A3} is a 3 dimensional coefficient of active earth pressure, see Equation 26.5;
u is the pore pressure, in kN/m^2, see Equation 29.4;
σ'_{h} is the effective horizontal soil pressure at the shield center, in kN/m^2;
σ'_{v} is the effective vertical stress at the shield center, in kN/m^2, see Equation 29.5. In case of arching effect over the depth C_1 (i.e. $C_1/D_{\text{o}} > f_{\text{silo}}$), the vertical effective stress σ'_{v} is reduced to $\sigma'_{\text{v;1}}$ as explained below (see Equation 26.6).

The 3 dimensional coefficient of active earth pressure is calculated as follows:

$$K_{\text{A3}} = \frac{\sin\beta \times \cos\beta - \cos^2\beta \times \tan\varphi - \frac{2}{3}K \times \alpha \times \cos\beta \times \tan\varphi}{\cos\beta \times \sin\beta + \tan\varphi \times \sin^2\beta} \tag{26.5}$$

with:

$$\alpha = \frac{1 + 3\frac{C_1}{D_o}}{1 + 2\frac{C_1}{D_o}}$$

where:

- C_1 is the distance between the drained/undrained border and the top of the shield of the micro tunneling machine, in m;
- β is the angle of the slip surface of the active wedge, in degree;
- φ is the angle of internal friction, in degree.

In the subsequent figure the values for different angles of internal friction for a series of depth/diameter ratios are shown.

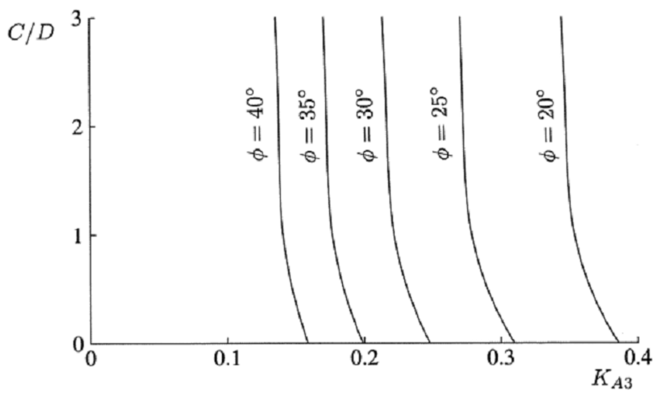


Figure 26.2: *Values for K_{A3}*

The method described by Jancsecz and Steiner Jancesz and Steiner (1994) has the opportunity to take the effect of vertical stress reduction due to arching in account. In Figure 26.3, the arching over the depth C can reduce the vertical stress on the active wedge which determines the minimal support pressure. It should be noticed that the arching can only occur if a relative small soil deformation (settlement of the soil column above the active soil wedge) is allowed.

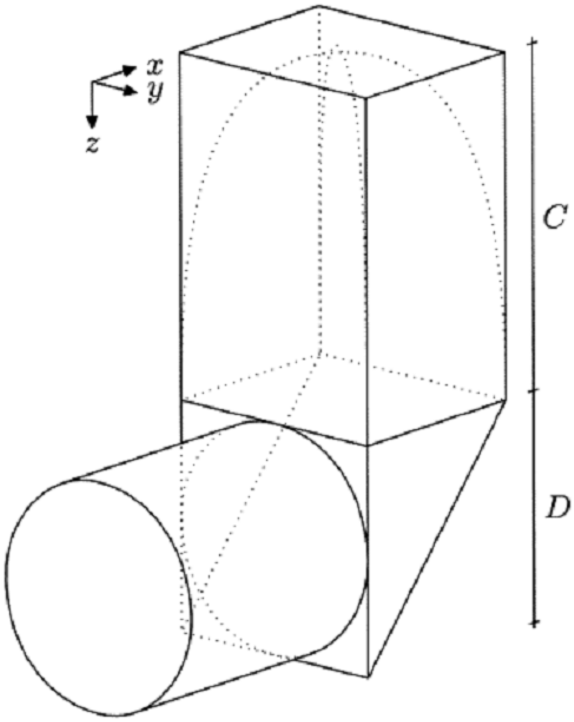


Figure 26.3: *Active soil wedge with soil column (Broere, 1994)*

For a layered soil the following equation can be used to calculate the effect of two dimensional arching according to Terzaghi (Terzaghi, 1943) on the active wedge:

$$\sigma'_{\text{v;1}} = \frac{\frac{A}{O} \times \gamma' - c_{\text{d}}}{K_0 \times \tan \varphi_{\text{d}}} \left[1 - \exp \left(-\frac{O}{A} \times C_2 \times K_0 \times \tan \varphi_{\text{d}} \right) \right] + \frac{D_{\text{o}}}{2} \times \gamma'_{\text{b}} \quad (26.6)$$

with:

$$\frac{O}{A} = \frac{2 \left[1 + \tan \left(\frac{\pi}{2} - \beta \right) \right]}{D_{\text{o}} \times \tan \left(\frac{\pi}{2} - \beta \right)}$$

where:

A	is the area of the soil column, in m^2;
c_{d}	is the cohesion of the slip surface of the active wedge (i.e. average between the drained/undrained border and the top of the shield of the micro tunneling machine), in kN/m^2;
C_2	is the distance between the ground level and the top of the shield of the micro tunneling machine, in m;
K_0	is the coefficient of neutral earth pressure: $K_0 = 1 - \sin \varphi_{\text{d}}$;
O	is the circumference of the soil column, in m;
φ_{d}	is the average angle of internal friction between the drained/undrained border and the top of the shield of the micro tunneling machine, in degrees;
γ'	is the average effective unit weight between the ground level and the top of the shield of the micro tunneling machine, in kN/m^3;
γ'_{b}	is the average effective unit weight between the top and the center of the shield of the micro tunneling machine, in kN/m^3.

26.1.3 Maximal support pressure

In case of a high support pressure, several possible failure mechanism may occur:

◇ Soil failure due to pushing a soil wedge in upward direction
◇ A blow out to the surface due to hydraulic fracturing
◇ Horizontal hydraulic fracturing at the transition of soil layers

The maximal allowable support pressure σ_{max} for micro tunneling can be determined as follows:

$$\sigma_{\text{max}} = \frac{\sigma'_{\text{v}}}{f_{\text{cover}}} + u \times f_{\text{u}} \tag{26.7}$$

where:

σ'_{v}	is the effective vertical stress (see Equation 29.5);
u	is the pore pressure, in kN/m^2, see Equation 29.4;
f_{cover}	is the contingency factor on soil cover as defined in the *Factors* window, see section 4.7.1.2 (default is 1.1).
f_{u}	is the safety factor on water pressure as defined in the *Factors* window, see section 4.7.1.2 (default is 1.05);

Obvious the total allowable support pressure is equal to the sum of the allowable effective support pressure and the water pressure at the drilling line.

26.1.4 Thrust force

The thrust force which is required to install a pipeline or micro tunnel in between the launch pit and the reception pit. The magnitude of the thrust force is determined by the pressure on the shield (head of the tunneling machine) and friction along the circumference of the tunnel or pipeline. The thrust force due to pressure on the shield is relative small compared to the force due to friction and can therefore be neglected. The thrust force F_{m} due to friction can be calculated as follows:

$$F_{\text{m}} = \pi \times D_{\text{o}} \times L \times M \tag{26.8}$$

where:

D_{o}	is the diameter of the pipeline or the tunnel, in m;
L	is the length, in m;
M	is the friction between the soil and the pipe per surface area, in kN/m^2. The friction M is defined in the *Engineering Data* window (section 4.6.3.3) where two cases are considered: friction with or without injection of lubricant.

The friction per surface area is partly determined by the soil type, through which the micro tunneling is carried out, but is mainly determined by the overcut and the usage of lubricants, which reduce the friction in between the tunnel or pipeline and the surrounding soil. Since the bending radii of the curves in a micro tunneling drilling line are generally smooth the soil reaction forces in the curves are not considered in D-GEO PIPELINE.

26.2 Uplift Safety

Due to buoyancy of the pipeline below the groundwater table, the uplift should be checked:

$$f_{\text{uplift}} < f_{\text{uplift;all}} \tag{26.9}$$

where $f_{\text{uplift;all}}$ is the allowable safety factor on uplift, as defined in the *Factors* window, see section 4.7.1.2.

The forces acting on the pipeline are:

◇ the uplift force:

$$g_{\text{uplift}} = \frac{\pi}{4} \times D_{\text{o}}^2 \times \gamma_{\text{w}} \tag{26.10}$$

◇ the weight of the pipeline:

$$g_{\text{pipe}} = \frac{\pi}{4} \times \left[D_{\text{o}}^2 - (D_{\text{o}} - 2d_{\text{n}})^2\right] \times \gamma_{\text{b}} \tag{26.11}$$

The effective weight of the pipeline is defined as:

$$g_{\text{eff}} = g_{\text{pipe}} - g_{\text{uplift}} \tag{26.12}$$

and the uplift safety factor f_{uplift} is:

$$f_{\text{uplift}} = \frac{g_{\text{eff}}}{\sum_{i=1}^{n} \gamma_{\text{i}}' \times d_{\text{i}}} \tag{26.13}$$

where:

γ_{i}' is the buoyant unit weight of soil layer i, in kN/m^3;
n is the number of soil layers;
d_{i} is the thickness of soil layer i above the pipeline, in m.

26.3 Subsidence

The drilling process micro tunneling leads to a larger amount of removed soil material than the volume of the installed tunnel or pipeline (Overcut). Of course injection of lubricants may lead to a reduction of the differential volume of removed soil and installed elements. The differential volume will lead to soil movement towards the bore hole, which in turn will lead to subsidence. The magnitude of the subsidence w (trough shaped) can be calculated as follows:

$$w = \frac{V_{\text{s}}}{\sqrt{2\pi i^2}} \exp\left(-\frac{r^2}{2i^2}\right) \qquad z < z_0 \tag{26.14}$$

with:

$$V_{\text{s}} = \frac{V_{\text{loss}}}{100} \times \left[\left(\frac{D_{\text{o}} + 2\, l_{\text{overcut}}}{2}^2\right) - \left(\frac{D_{\text{o}}}{2}^2\right)\right]$$

where:

i is the shape factor, see below;

l_{overcut} is the overcut in radius, in m;
r is the horizontal distance in between the center of the tunnel or pipeline and the inflection point of the trough, in m;
z_0 is the depth of the center of the pipeline or tunnel, in m;
z is the depth at which the settlement is calculated, in m;
V_{loss} is the volume loss as percentage of overcut area, in %, as defined in the *Engineering Data* window, see section 4.6.3.2;
V_{s} is the differential volume, in m^3/m.

The shape factor i depends upon the soil behavior above the tunnel or pipeline and is there dependent upon the soil properties of the upper soil layers. The factor i can empirically be determined based on differences in soil sequences. The empirical method is described by O Reilly (O' Reilly and New, 1982):

$i = 0.43\,D_{\text{bas}} + 0.28\,D_{\text{top}} + 1.1$	for incompressible granular soil on compressible soil
$i = 0.43\,D_{\text{bas}} + 1.1$	for compressible soil
$i = 0.23\,D_{\text{bas}} + 0.43\,D_{\text{top}} - 0.1$	for compressible soil on incompressible granular soil
$i = 0.28\,D_{\text{bas}} - 0.1$	for incompressible granular soil

where:

D_{bas} is the thickness of the Basal layer above the tunnel or pipeline, in m;
D_{top} is the thickness of the upper layer above the tunnel or pipeline, in m.

27 Trenching

Installation of the pipeline in a trench is the oldest and a relatively easy method. One of the main installation risk associated with trenching is instability of the slopes of the trench. This risk can not be considered in D-GEO PIPELINE. Use of other computer programs such as D-GEO STABILITY (formerly known as MStab) is recommended.

In case of installed pipelines with a relatively thin soil cover in a wet environment, uplift can be an installation risk (section 27.1). In case of trenching in soil layers which cover an aquifer with high pore pressures, bursting of the bottom of the trench (heaving) can be an installation risk (section 27.2).

27.1 Uplift Safety

Due to buoyancy of the pipeline below the groundwater table, the uplift should be checked:

$$f_{\text{uplift}} < f_{\text{uplift;all}} \tag{27.1}$$

where $f_{\text{uplift;all}}$ is the allowable safety factor on uplift, as defined in the *Factors* window, see section 4.7.1.3.

The forces acting on an empty pipe are:

- ◇ the uplift force:

$$g_{\text{uplift}} = \frac{\pi}{4} \times D_{\text{o}}^2 \times \gamma_{\text{w}} \tag{27.2}$$

- ◇ the weight of the pipeline:

$$g_{\text{pipe}} = \frac{\pi}{4} \times \left[D_{\text{o}}^2 - (D_{\text{o}} - 2d_{\text{n}})^2 \right] \times \gamma_{\text{b}} \tag{27.3}$$

The effective weight of the pipeline is defined as:

$$g_{\text{eff}} = g_{\text{pipe}} - g_{\text{uplift}} \tag{27.4}$$

and the uplift safety factor f_{uplift} is:

$$f_{\text{uplift}} = \frac{g_{\text{eff}}}{\sum_{i=1}^{n} \gamma_{\text{i}}' \times d_{\text{i}}} \tag{27.5}$$

where:

γ_{i}'	is the buoyant unit weight of soil layer i, in kN/m^3;
n	is the number of soil layers;
d_{i}	is the thickness of soil layer i above the pipeline, in m.

27.2 Bursting of the trench bottom (heaving)

The check of the bursting of the trench bottom is performed according to paragraph 14.3.1 of the Dutch standard NEN 6740:2006 (NEN, 2006). The calculated safety factor f_{burst} should not exceed the allowable safety factor on hydraulic heave $f_{\text{burst;all}}$, as defined in the *Factors* window, see section 4.7.1.3.

$$f_{\text{burst;all}} > f_{\text{burst}} \tag{27.6}$$

The safety factor on bursting f_{burst} is:

$$f_{\text{burst}} = \frac{W_{\text{tot}}}{p_{\text{z;d}}} \tag{27.7}$$

where:

$p_{\text{z;d}}$ is the upward water pressure, in kN/m^2, see Equation 27.11.
W_{tot} is the total weight above the aquifer, in kN/m^2, see Equation 27.8;

Total weight above the aquifer

$$W_{\text{tot}} = W_{\text{tot;1}} + W_{\text{tot;2}} \tag{27.8}$$

$$W_{\text{tot;1}} = f \times \gamma_{\text{1;d}} \times d_{\text{1;d}} \tag{27.9}$$

$$W_{\text{tot;2}} = \sum_{j=1}^{n} \gamma_{\text{j;d}} \times d_{\text{j;d}} \tag{27.10}$$

with:

$$f = \frac{2}{\pi}\left[\left(1+\frac{b}{a}\right) \times \arctan\left(\frac{d_{\text{2;d}}}{a+b}\right) - \frac{b}{a} \times \arctan\frac{d_{\text{2;d}}}{b}\right]$$

where:

a is the width (horizontally) of the slope of the trench, in m;
b is the depth of the slope of the trench, in m;
$d_{\text{1;d}}$ is the sum of the thickness of the layers above the excavation level, in m;
$d_{\text{2;d}}$ is the sum of the thickness of the layers below the pipe (excavation level) and above the aquifer, in m.
f is the factor for the contribution of the layers above the excavation level according to Figure 27.2;
$W_{\text{tot;1}}$ is the weight of the soil layers above the trench bottom, in kN/m^2;
$W_{\text{tot;2}}$ is the weight of the overburden soil layers below the trench bottom, in kN/m^2;
$\gamma_{\text{1;d}}$ is the average unit weight of the layers above the excavation level, in kN/m^3;

Upward water pressure

$$p_{\text{z;d}} = H_{\text{d}} \times \gamma_{\text{w}} \tag{27.11}$$

where:

H_d is the hydraulic head with respect to the upper boundary of the aquifer, calculated according to section 29.1;

γ_w is the unit weight of water, in kN/m^3.

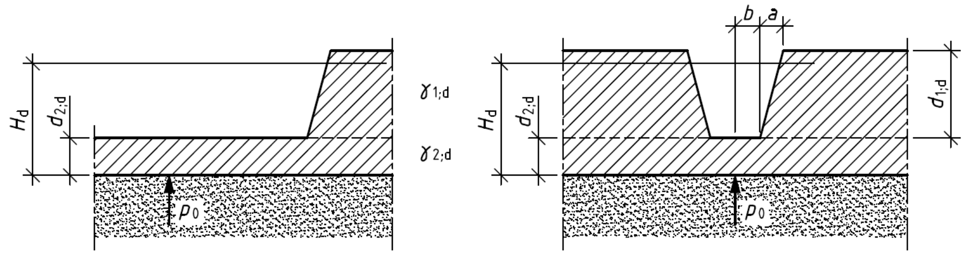


Figure 27.1: *Definition of parameters H_d, $d_{1;d}$ and $d_{2;d}$ (Figure 18 of NEN 6740:2006)*

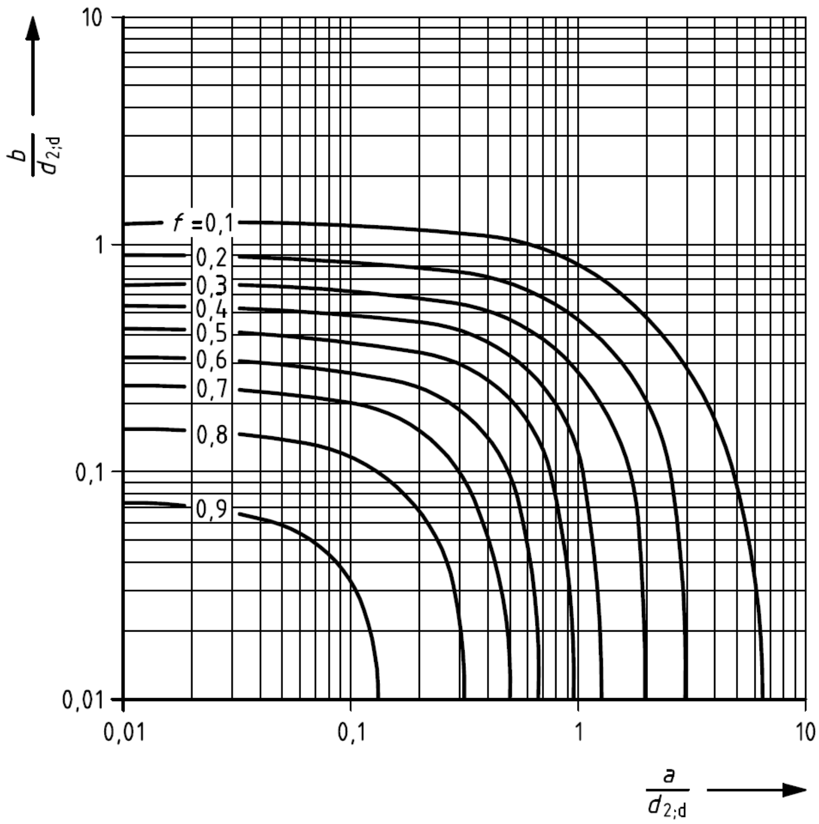


Figure 27.2: *Factor f for the contribution of the layers above the bottom of the excavation (Figure 19 of NEN 6740:2006)*

28 Direct Pipe

This chapter describes the mechanisms that contribute to the thrust force in the Direct Pipe Method (DPM).

28.1 Friction force mechanisms and their interaction

A thrust force is needed to push the pipeline into the borehole, because of mechanisms that cause the pipeline to have friction. There are 5 mechanisms that contribute to this friction:

- Mechanism 1: Friction of the pipeline behind the thruster on the rollers (section 28.1.1)
- Mechanism 2: Friction between pipeline and lubricant/drilling fluid (section 28.1.2)
- Mechanism 3: Front force at the cutting head
- Mechanism 4: Friction between pipeline and the borehole wall (section 28.1.3)
- Mechanism 5: Friction due to the buckling of the pipe (section 28.1.4)

There is an interaction between these mechanisms, but the first mechanism is uncoupled because the pipeline on the rollers produces is behind the thruster. The thruster pulls that section of the pipeline, and in front of the thruster the pipeline is pushed. The friction of the rollers is just added to total force that must be delivered by the thruster, but doesn't influence the thrust force in front of the thruster.

Mechanisms 2 and 3 interact with mechanism 4, because the overall thrust force creates "capstan" forces in the bend section of the borehole. The pushing force can reduce (or increase depending on the situation) the pressure of the pipeline against the borehole wall, thereby decreasing (or increasing) the friction.

The first two mechanisms are using formulas that are based on the NEN 3650, which describes calculating pullback forces for horizontal directional drilling of pipelines (HDD). The third mechanism, the front force, is using a theoretical formula. The formulas of the first two mechanisms are described in sections section 28.1.1 and section 28.1.2. The third mechanism is described in section 26.1.1, section 26.1.2 and section 26.1.3. The latter two are described in section 28.1.3 and section 28.1.4.

28.1.1 Friction of the pipeline behind the thruster on the rollers

The NEN 3650 provides the following friction formula for the section of the pipeline that is outside of the borehole:

$$\Delta F_{\text{w}} = L_{\text{o}} \times g_{\text{p}} \times f_1 \tag{28.1}$$

ΔF_{w} is the contribution to the friction force, L_{o} the length of the pipeline outside the borehole up to the thruster, g_{p} is the weight of the pipeline per unit length and f_1 is the friction coefficient. If the pipeline is on rollers the NEN 3650 suggest using f_1 = 0.1, if the pipeline rests on the surface, a value f_1 = 0.3 is suggested.

28.1.2 Friction between pipeline and lubricant/drilling fluid

The NEN 3650 provides the following formula for the friction between lubricant and pipeline:

$$\Delta F_{\text{w}} = L_{\text{b}} \times \pi \times D_{\text{o}} \times f_2 \tag{28.2}$$

ΔF_{w} is the contribution to the friction force, L_{b} the total length of the pipeline in the borehole. This is the length along the borehole from the thruster to the cutting head. D_{o} is the outer

diameter of the borehole and f_2 is the friction between drilling fluid and the pipeline expressed in force per area unit, sometimes also called the yield strength of the lubricant. It can be seen that according to this formula this friction is just the total outside area of the pipeline inside the borehole times a friction per area value. The NEN suggests f_2 = 50 N/m^2. For the DPM this value is considered a bit too conservative. D-GEO PIPELINE uses a value of f_2 =100 N/m^2

28.1.3 Friction between pipeline and borehole wall

Friction between the pipeline and borehole wall is modelled by multiplying the force that the pipeline exerts on the soil (perpendicular to the borepath) by a friction coefficient. The friction always acts parallel to the borepath in the opposite direction of the pushing. This can be expressed as:

$$\Delta F_{\mathsf{w}} = f_3 \int_{L_{\mathsf{b}}}^{0} |q(s)|\, ds \tag{28.3}$$

Here q is the soil reaction perpendicular to the pipeline as a function of the distance along the borepath s. The value of f_3 is the friction coefficient between pipeline and soil, the NEN 3650 suggests f_3 = 0.2. For the DPM this value is considered a bit too conservative, therefore D-GEO PIPELINE uses a value of f_3 = 0.3. In case of collapse of the borehole a value of f_3 = 0.6 is recommended. The integral is along the borepath from the thruster (zero) to L_{b} , the total length of the pipeline inside the borehole.

The value of q can be positive or negative, depending on whether the pipeline touches the upper or lower borehole wall (in fact in a 3D situation q is not a scalar but a vector as the pipeline can also touch the borehole sideways. But this is not taken into account here, since a 2D borepath is assumed.)

28.1.4 Friction due to the buckling of the pipe

The pipeline can buckle in length direction, the additional friction caused by buckling can be calculated with:

$$F_{\mathsf{buckle}} = f_3\, \frac{4}{3} \frac{L \times F^2}{\pi^2 EI}\, w_{\mathsf{gap}} \tag{28.4}$$

F is the calculated thruster force without buckling, L is the total length of the pipeline inside the borehole, EI is the bending stiffness of the pipeline and w_{gap} is the borehole diameter minus the pipeline outer diameter.

28.2 Design rules for the thrust force

28.2.1 Bore-path geometry

A bore-path with two bends and three straight sections is assumed. The path is defined according to Figure 28.1.

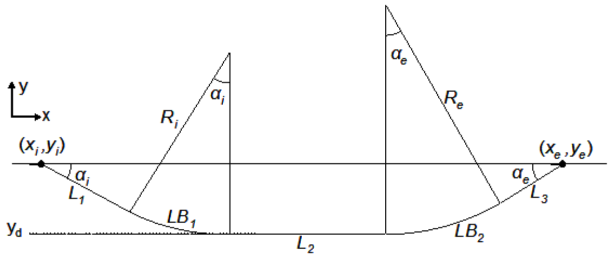


Figure 28.1: *Bore-path definition*

The following parameters define the bore-path completely:

$(x_\mathrm{i},y_\mathrm{i})$	is the entry point of the bore-path;
α_i	entry angle (with x-axis) of the bore-path;
R_i	is the radius of the bend section;
y_d	is the vertical position of the deepest point of the bore-path;
R_e	is the radius of second bend section;
α_e	is the exit angle (with x-axis) of the bore-path;
$(x_\mathrm{e},y_\mathrm{e})$	is the exit point of the bore-path.

From these parameters, the lengths of the five sections, L_1, LB_1, L_2, LB_2, L_3 can be determined, of which LB_1 and LB_2 are arc lengths. These lengths will be used in subsequent paragraphs where convenient.

28.2.2 List of input parameters

The other parameters used in these design rules are:

EI	bending stiffness of the pipeline in Nm^2;
k	soil stiffness per length of pipeline in N/m^2;
g_p	weight of pipeline per length unit in N/m;
g_m	weight of machine per length unit in N/m;
g_eff	net weight of pipeline in the fluid per length of pipeline in N/m;
$g_\mathrm{eff,m}$	net weight of machine in the fluid per length of pipeline in N/m;
D_o	outer diameter of the pipeline;
$D_\mathrm{o,m}$	outer diameter of the machine;
L_m	length of the machine;
w_gap	the borehole diameter minus the pipeline outer diameter;
F_mechanic	the mechanical pressure needed for cutting at the cutting head times the area to obtain a mechanical front force. This will be added to the front force;
f_1	friction coefficient of roller track;
f_2	friction between pipeline and fluid (yield strength) per area in N/m^2;
f_3	friction coefficient pipeline and borehole wall;

28.2.3 Friction of the machine

28.2.3.1 Front force calculation

The front force if based on the maximum allowable support pressure for tunneling below n soil layers. This is determined using the following steps:

- Calculate the maximum effective support pressure:

$$\sigma'_{\text{max}} = \sum_{\text{i=1}}^{\text{n}} \gamma'_{\text{i}} \times d_{\text{i}} \tag{28.5}$$

where γ'_{i} is the buoyant weight of soil layer i in kN/m^3, n the number of soil layers and d_{i} the thickness of soil layer i above the cutting head in m.

- Calculate the maximum support pressure:

$$\sigma_{\text{max}} = \sigma'_{\text{max}} + h_{\text{w}} \times \gamma_{\text{w}} \tag{28.6}$$

where γ_{w} is the unit weight of water in kN/m^3 and h_{w} is the height of water column above the cutting head.

- Calculate the maximum allowable front force:

$$F_{\text{m1}} = \sigma_{\text{max}} \, \frac{\pi}{4} \, D^2_{\text{0,m}} \times F_{\text{mechanic}} \tag{28.7}$$

This front force depends on the location of the machine in the borepath and can be calculated for various locations.

28.2.3.2 Friction in lubricant and machine borehole wall contact

Use the following formula to calculate the total friction of the machine:

$$F_{\text{m2}} = L_{\text{m}} \times (\pi D_{\text{o,m}} \times f_2 + |g_{\text{eff,m}}| \times f_3) \tag{28.8}$$

28.2.4 Friction in straight sections of the borepath

Use the formula below to calculate the friction of the pipeline in the fluid and the friction of pipeline borehole wall contact for the three straight sections:

$$F_{\text{p}} = L \times (\pi D_{\text{o}} \times f_2 + |g_{\text{eff}}| \, f_3) \tag{28.9}$$

where L is the length of the pipeline in the straight section, which differs per section, and depends on whether the machine is also in a section.

The thruster boundary condition also effects this length, in the first section of the borehole the following formula needs be used:

$$F_{\text{p}} = L_1 \times (\pi D_{\text{o}} \times f_2 + |g_{\text{eff}}| \times f_3) - L_{\text{t}} \times |g_{\text{eff}}| \times f_3 \tag{28.10}$$

where L_{t} is calculated according to the next section. The above is valid if the machine is not in the first section. There needs to be special considerations if the machine IS in the first section.

28.2.4.1 Thruster boundary condition

Calculate the length over which the pipeline is free from the borehole wall from the thruster, if $g_{\text{eff}} \neq 0$.

$$L_{\text{t}} = \sqrt[4]{\frac{8EI \times w_{\text{gap}}}{|g_{\text{eff}}|}} \tag{28.11}$$

If $g_{\text{eff}} = 0$, the length is irrelevant.

28.2.5 Friction on the rollertrack

Calculate the friction on the roller track by:

$$F_{\text{r}} = L \times g_{\text{p}} \times f_1 \tag{28.12}$$

where L is the length of the pipeline on the roller track.

28.2.6 Friction due to entry and exit of the bends

Each of the two bends has an entry and exit point, at each of these there is a soil reaction due to bending of the beam. For the entry or exit of the first bend this is calculated using the following steps:

Determine the maximum soil reaction due to bending if no net weight is present:

$$q_{\text{max}} = \frac{EI\lambda^2}{R_{\text{i}}} e^{-\pi/4} \sin(\frac{\pi}{4}) = 0.3224 \frac{EI\lambda^2}{R_{\text{i}}} \tag{28.13}$$

where: $\lambda = \sqrt[4]{\frac{k}{4EI}}$

Then determine: $a = \left| \frac{g_{\text{eff}}}{q_{\text{max}}} \right|$, if $a > 1$ set $a = 1$.

Then calculate the contribution of the friction with:

$$\Delta F_{\text{w}}^{\text{bend}} = \frac{f_3 EI\lambda}{R_{\text{i}}} (0.85a - 1.903) \times (a - 1) \tag{28.14}$$

For the friction of the second bend use R_{e} instead of R_{i} in the equations above.

28.2.7 Friction in curved sections

Calculate the total force at the end of the bend. First determine the total friction force F_{p}^0 at the beginning of the bend.

28.2.7.1 Case I

If $g_{\text{eff}} R > F_{\text{p}}^{0}$ then calculate the total friction force at the end of the bend using the following equations, if not calculate the total friction force according to Case II.

$$F_{\text{p}}^{\text{end}} = \frac{c_1}{f_3} + (F_{\text{p}}^{0} - \frac{c_1}{f_3}) \exp^{f_3 \alpha}$$
$$c_1 = \pi D_{\text{o}} \times f_2 \times R + f_3 \times R \times g_{\text{eff}}$$

Here $R = R_1$ and $\alpha = \alpha_{\text{i}}$ for the first bend of use the index e when calculating the second bend. Check that $g_{\text{eff}} \times R \geq F_{\text{p}}^{\text{end}}$, if this is not true use Case II.

28.2.7.2 Case II

In the situation that $g_{\text{eff}} \times R \leq F_{\text{p}}^{0}$ (which is always the case if g_{eff} is negative), or when first using case I and finding: $g_{\text{eff}} \times R < F_{\text{p}}^{\text{end}}$, use the following equation to calculate the total friction force at the end of the bend:

$$F_{\text{p}}^{\text{end}} = \frac{-c_1}{f_3} + (F_{\text{p}}^{0} + \frac{c_1}{f_3}) \exp^{f_3 \alpha}$$
$$c_1 = \pi \; D_{\text{o}} \times f_2 \times R - f_3 \times R \times g_{\text{eff}}$$

Here $R = R_1$ and $\alpha = \alpha_{\text{i}}$ for the first bend or use the index e when calculating the second bend.

28.2.8 Buckling

The pipeline can buckle in length direction, the additional friction caused by buckling can be calculated with:

$$F_{\text{buckle}} = f_3 \frac{4}{3} \frac{L F^2}{\pi^2 E I} w_{\text{gap}} \tag{28.15}$$

F is the calculated thruster force without buckling. L is the total length of the pipeline inside the borehole.

28.2.9 Adding the friction components to obtain the overall friction force

Dependent on the location of the machine, calculate first the total friction due to the machine, $F_{\text{m1}} + F_{\text{m2}}$. If there is a straight section between the bend behind the machine and the end of the machine, calculate the additional friction F_{p} of that piece of pipeline. Then if there is a bend, add the additional friction force $F_{\text{w}}^{\text{bend}}$ calculated with the correct radius of that bend. This gives the total force $F_{\text{m1}} + F_{\text{m2}} + F_{\text{p}} + F_{\text{w}}^{\text{bend}}$ just before the bend. Apply the formula for case I or case II to compute $F_{\text{p}}^{\text{end}}$ at the end of the bend. Then add $F_{\text{w}}^{\text{bend}}$ to that and continue with adding the friction of the next straight section using the formula for F_{p} with the correct length. Then calculate $F_{\text{w}}^{\text{bend}}$ using the radius of the second bend and add it to the total before applying the formula for the bend (case I or case II) to find $F_{\text{p}}^{\text{end}}$ at the end of the second bend. Then add a final friction of the last straight section using the formula for F_{p} with the correct length, paying attention to the thruster boundary condition. This gives the total force before the thruster. Use this force in the buckling formula to calculate F_{buckle} and add it to the total force. Add the friction on the roller track F_{r} if any. This gives the total needed thruster force.

29 Effective Stress and Pore Pressure

29.1 Hydraulic head from piezometric level lines

A piezometric level line (PL-line) represents the initial and transient hydraulic water heads in the soil, excluding the excess component. Several PL-lines can be defined in the *PL-Lines* window (section 4.3.10). A PL-line for the top and bottom of each soil layer can be defined in the *Pl-lines per Layer* window (section 4.3.13).

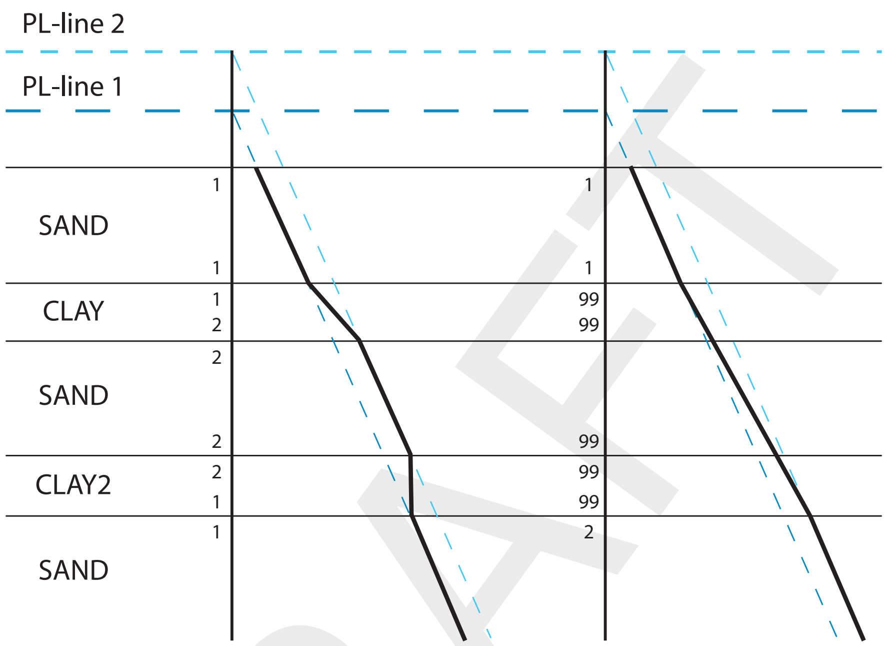


Figure 29.1: *Pore pressure as a result of piezometric level lines*

D-GEO PIPELINE calculates the hydraulic pore pressure along a vertical in the following way:

The pore pressure inside a layer is calculated by linear interpolation between the pore pressures at the top and bottom. The pore pressure at the top or bottom is equal to the vertical distance between this point and the position of the PL-line that belongs to this layer, multiplied by the unit weight of water.

If PL-line number 99 is specified for the top and/or bottom of any soil layer, at that boundary D-GEO PIPELINE will use the PL-line of the nearest soil layer above or below, which has a thickness larger than zero and a PL-line number not equal to 99. If the interpolation point is located above the phreatic line, the pore pressure is assumed to be zero or a capillary pressure, depending on the sign of the PL-line number. The following options are available, therefore, for PL-line numbers:

- ◇ **Positive integer**:
  Capillary pore pressures are not used – that is, if negative pore pressures are calculated for points above the phreatic line they become zero;
- ◇ **Zero**:
  All points within the layer obtain a pore pressure of 0 kN/m;
- ◇ **99**:
  The pore pressure depends on the first layer above and/or below the point with a PL-line

number unequal to 99.

29.2 Phreatic line

The phreatic line (or groundwater level) marks the border between dry and wet soil. The phreatic line is treated as if it was a PL-line, and can also be used as such. The PL-line acting as the phreatic line is determined while the geometry is being defined. If no phreatic line is entered, then all the soil is assumed to be dry.

29.3 Stress by soil weight

The total stress at depth z due to soil weight is:

$$\sigma_{\text{soil}}(z) = \begin{cases} \gamma_{\text{unsat}} \times z & \text{if } z > z_{\text{water}} \\ \gamma_{\text{unsat}} \times z_{\text{water}} + \gamma_{\text{sat}} \times (z_{\text{water}} - z) & \text{if } z \leq z_{\text{water}} \end{cases} \tag{29.1}$$

where:

γ_{unsat}	is the unit weight of soil above phreatic level, in kN/m^3;
γ_{sat}	is the unit weight of soil below phreatic level, in kN/m^3;
z	is the vertical co-ordinate, in m;
z_{water}	is the vertical co-ordinate of the phreatic level, in m.

29.4 Distribution of stress by loading

D-GEO PIPELINE uses Boussinesq's formula (Boussinesq, 1885) to determine the additional vertical stress due to the surcharge loads.

29.4.1 Stress increment caused by a line load

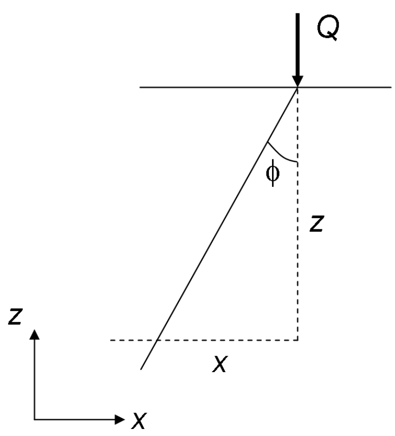


Figure 29.2: *Stress distribution under a load column*

The vertical stress increment $\Delta\sigma_z$ due to a line load Q is:

$$\Delta\sigma_z = \frac{2}{\pi}\frac{Q}{z}\cos^4\phi \tag{29.2}$$

where:

z is the depth, in m;

Q is the line load, in kN;
ϕ is the angle with the vertical, in radians.

29.4.2 Stress increment caused by a strip load

The stress increments in a point (x, y) due to a strip load can be found by integration of the line load along the width 2 dx of the strip load in Equation 29.2:

$$\Delta\sigma_{\text{load}} = \frac{q}{\pi}\left[(\phi_1 - \phi_2) + \sin\phi_1\cos\phi_1 - \sin\phi_2\cos\phi_2\right] \tag{29.3}$$

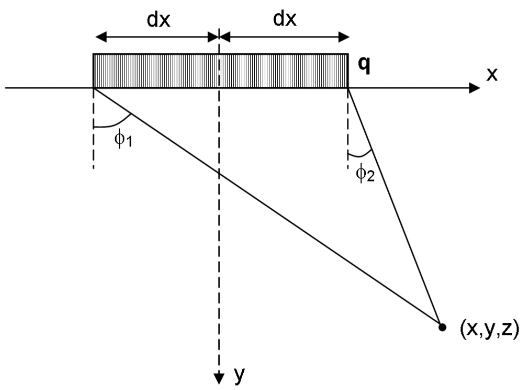


Figure 29.3: *Stress distribution under a load column*

29.5 Effective stress and pore pressure

The pore pressure u at vertical position z is defined as:

$$u(z) = \sigma_{\text{water}}(z) - \max\left[h(z) - z; 0\right] \times \gamma_{\text{w}} \tag{29.4}$$

The effective stress σ' at vertical position z is defined as:

$$\sigma'(z) = \sigma_{\text{soil}}(z) + \Delta\sigma_{\text{load}}(z) - u(z) \tag{29.5}$$

with:

$$\sigma_{\text{water}}(z) = \max\left(z_{\text{water}} - z_{\text{surface}}; 0\right) \times \gamma_{\text{w}}$$

where:

z is the vertical co-ordinate, in m;
z_{water} is the vertical position of the phreatic level , in m;
z_{surface} is the vertical position of the ground level , in m;
h is the user-defined hydraulic head in the *Pl-lines per Layer* window (section 4.3.13), see section 29.1;
σ_{soil} is the stress due to soil weight, in kN/m^2, see Equation 29.1;
σ_{water} is the stress due to a water level above the soil surface, in kN/m^2;
$\Delta\sigma_{\text{load}}$ is the incremental stress due to loads, in kN/m^2, see Equation 29.3.

30 Benchmarks

Deltares Systems commitment to quality control and quality assurance has leaded them to develop a formal and extensive procedure to verify the correct working of all of their geotechnical engineering tools. An extensive range of benchmark checks have been developed to check the correct functioning of each tool. During product development these checks are run on a regular basis to verify the improved product. These benchmark checks are provided in the following sections, to allow the user to overview the checking procedure and verify for themselves the correct functioning of D-GEO PIPELINE. The benchmarks are subdivided into five separate groups as described below.

- **Group 1 – Benchmarks from literature (exact solution)** Simple benchmarks for which an exact analytical result is available from literature.
- **Group 2 – Benchmarks from literature (approximate solution)** More complex benchmarks described in literature for which an approximate solution is known.
- **Group 3 – Benchmarks from spread sheets** Benchmarks which test program features specific to D-GEO PIPELINE.
- **Group 4 – Benchmarks generated by D-GEO PIPELINE** Benchmarks for which the reference results are generated using D-GEO PIPELINE.
- **Group 5 – Benchmarks compared with other programs** Benchmarks for which the results of D-GEO PIPELINE are compared with the results of other programs.

The number of benchmarks in group 1 may grow in the future. The benchmarks in this chapter are well documented in literature. There are no exact solutions available for these problems, however in the literature estimated results are available. When verifying the program, the results should be close to the results found in the literature. The number of benchmarks in group 2 will grow as new versions of the program are released. These benchmarks are designed so that (new) features specific to the program can be verified. The benchmarks are kept as simple as possible so that only one specific feature is verified from one benchmark to the next. As much as software developers would wish they could, it is impossible to prove the correctness of any non-trivial program. Re-calculating all the benchmarks, and making sure the results are as they should be, proves to some degree that the program works as it should. Nevertheless, there will always be combinations of input values that will cause the program to crash or to produce wrong results. Hopefully by using the verification procedure the number of ways this can occur will be limited. The benchmarks are all described in details in the *Verification Report* available in the installation directory of the program.

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